THERMIONIC TUBES

IN

Radio Telegraphy and Telephony

BY

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PREFACE.

The thermionic vacuum tube or valve has, within the last few years, become such an important feature of wireless practice and development that modern radio communication may almost be said to be the application of this versatile device to the reception and transmission of wireless signals. The present book has been written with a view to providing in a single volume an account of the practical development of the vacuum tube and its innumerable applications.

An attempt has been made to arrange the matter in a logical manner, and also to give historical details of interest. Every attempt has also been made to give references to the work of those who have developed the science by their inventions or scientific contributions.

While writing from a practical experience of nearly all the matter contained in this volume, the Author has taken the fullest advantage of the work of others, with a view to making the book as comprehensive and detailed as possible. A great many references are given, and if any which should have been given are omitted it is due solely to the large size of the volume. In this connection, great difficulty has been experienced in allocating the credit for different developments on account of the absence of international exchange of information. Unless information is freely circulated by publication, misunderstandings as to the rightful credit for inventions are bound to arise. Nevertheless, the Author has made a thorough search of technical literature and patent specifications on the subject with a view to obtaining a correct perspective of the real work of development. Patent specifications particularly are of the greatest value.

although disregarded by most as a source of information. Since all the valuable inventions in connection with vacuum tubes have been described in patents, references to these have been given in full, partly to assist those who desire further information, and partly to give the chronological order of developments (the date governing priority being given after the patent number).

No pains have been spared to keep the volume up-to-date consistent with its size: a great deal of hitherto unpublished matter has been included. The constant and almost daily changes and developments of the art have necessitated repeated revisions and insertions right up to the date of going to press; but the laborious task of preparing a book of this nature and size will be considered as having been well worth while if the volume proves of value to those for whom it has been written.

It is hoped that there is something of value to all engaged in wireless work, from the engineer to the operator and experimentalist. The method of presenting the subject is such as to be easily understood by the student without previous experience; nevertheless, the subject is gradually expanded so as to cover the whole subject of valves in sufficient detail to make the student ultimately independent of a text-book. On a first reading a student would be well advised to leave out the more detailed information, preferably under the advice of a teacher.

Throughout the volume, theoretical circuits have been invariably followed by actual practical working arrangements. For the benefit of American readers, for whom the book has been equally written, many particulars of American circuits and sets have been given. About 350 diagrams, including many of a graphical nature, have been used to illustrate the text. The presentation of such an unusually large number of figures will, it is hoped, increase the value of the volume for many purposes.

The different terms for the vacuum tube have been used more or less indiscriminately, but preference has been given to the word "anode" instead of "plate." This is due to the growing dislike of calling a cylinder a plate.

The Author is much indebted to the Editors of the *Electrician*, *Electrical Review*, *Wireless Age*, *Wireless World*, and other journals for the reproduction of the substance of upwards of fifty articles by himself in these periodicals; also to E. E. Bucher for particulars of certain duplex telephone systems, and Monsieur Latour for information concerning certain amplifiers. Much information has also been obtained from valuable papers by Dr. W. H. Eccles, Prof. C. L. Fortescue, Dr. A. N. Goldsmith, H. J. Round, L. B. Turner, and others who have done much to further valve development, and who are too numerous to mention here, although the Author desires to acknowledge his indebtedness to them.

His concluding thanks are due to the Wireless Press, Ltd., for their uniform and excellent reproduction of his diagrams.

JOHN SCOTT-TAGGART.

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A CORRECTION

Page 10. After the words "V= potential difference between plate and filament" add "in volts."

Lower down, in the tables of electron velocity, 6,000 should read "60,000,000"; 60,000 should read "600,000,000," and 600,000 should read "6,000,000,000."

CHAPTER I.

TWO-ELECTRODE VALVES AND THE THEORY OF THERMIONIC CURRENTS.

I. **Thermionic Currents.**—Between the years 1882–1889 Elster and Geitel * carried out a series of systematic investigations of phenomena connected with the emission of electricity from hot bodies. They arranged a metallic filament and plate within a glass bulb which could be exhausted of air by means of a vacuum pump. The filament was heated by a battery, and means were provided for the measurement of any electrical charge received by the plate.

With the air inside the bulb at normal atmospheric pressure, the temperature of the filament was gradually increased by increasing the current passing through it. It was found that the plate received a positive charge of electricity which increased in value until the filament was at a yellow heat. When the temperature was raised above this value, the positive charge on the plate began to decrease until, at white heat, the charge became very small indeed. The pressure of the air inside the bulb was now reduced gradually, and it was noticed that the charge diminished still further until, at a critical temperature of the filament, it became negative, and this negative charge gradually increased as the exhaustion of

* In 1873, F. Guthrie carried out a series of experiments with the effect of a red and white hot metal ball on a charged electroscope, see *Phil. Mag.*, 4th series, xlvi. p. 257 (1873), "On a Relation between Heat and Static Electricity." These experiments led up to the important work of Elster and Geitel, described in the following references :–

"On the Electricity of Flames," *Wiedemann Annalen*, xvi. p. 193 (1882).

"On the Generation of Electricity by the Contact of Gases and Incandescent Bodies," *Wied. Ann.*, xix. p. 588 (1883).

"On the Unipolar Conductivity of Heated Gases," *Wied. Ann.*, xxvi. p. 1 (1885).

"On the Electrification of Rarefied Gases and Electrically Heated Wires," *Wied. Ann.*, xxxi. p. 109 (1887).

"On the Generation of Electricity by Contact of Rarefied Gas and Electrically Heated Wires," *Wied. Ann.*, xxxvii. p. 319 (1889).

the bulb continued. Later, it was found that the degree of electrification of the inserted plate, and also its sign, depended largely on the chemical nature of the substance forming the filament and also the nature of the gas inside the bulb. It was noticed that the presence of oxygen tended to reduce the charge received by the plate, while hydrogen favoured the reception of a negative charge by the plate, and even allowed it to receive such a charge at normal atmospheric pressure.

The next important step in the investigation of *thermionic currents*, which was the name given later to the electricity emitted from hot bodies, was the discovery made by Edison * in 1883, that if a plate be fitted inside an ordinary electric lamp and a galvanometer connected with one side to the plate and the other side to the positive of the battery heating the filament, a small current of one or two milliamperes will be registered by the galvanometer. This current appeared to flow from the positive side of the filament through the galvanometer to the plate and thence through the vacuum to the filament. The most interesting part of the experiment was the fact that practically no current flowed round the circuit if the galvanometer were connected across the plate and the *negative* side of the filament. Sir William Preece carried out further experiments on the Edison effect, which were described to the Royal Society of London in March, 1885.†

J. A. Fleming, in 1890, carried out further experiments and concluded that negative electricity flowed from the filament to the plate, if the latter were cold and at a higher potential than a portion of the filament. He also found that platinum was also capable of emitting electricity, though not to the same degree as carbon, of which substance Edison's filaments had been made.

It is interesting to note that, a little previously, W. Hittorf found that a small E.M.F. will send a measurable current through a vacuum tube provided the cathode is incandescent.‡

* See *Engineering*, Dec. 12, 1884, p. 553.

† See *Proc. Roy. Soc. Lond.*, XXXVIII. p. 219 (1885).

‡ See *Annalen der Physik*, XXI. p. 90 (1884): see also "Physical Memoirs," i. p. 180, issued by the Physical Society of London, W. Hittorf, "On Conduction of Electricity in Gases."

Further results of Fleming's work on the Edison effect are to be found in the *Philosophical Magazine*, July, 1896: also *Proc. Phys. Soc. Lond.*, XIV. p. 187 (1896).

No real clue as to the exact nature of this negative electricity was forthcoming until 1899, when Sir J. J. Thomson* proved to the world the actual existence of masses infinitely smaller even than atoms. He called these particles *corpuscles*, but they are now known under the name of *electrons*. He showed that the electricity emitted from heated filaments consisted of electrons.

The Electron.†—The electron, although of almost infinitely small size, has been indirectly measured and its mass is $1{\cdot}662 \times 10^{-24}$ grammes. It would take 1835 electrons to equal the mass of a hydrogen atom. The diameter of an electron has been estimated at $3{\cdot}7 \times 10^{-13}$ cm. and it would take 60,000 of them in line to equal the diameter of an atom of hydrogen. If the atom were magnified to the size of a large house the electron would possess the relative size of a small pellet. Each electron is considered to be a minute particle of negative electricity. It is considered as possessing a *unit charge*, which is the smallest known quantity of electricity and which corresponds to $4{\cdot}774 \times 10^{-10}$ of an electrostatic unit of quantity. Its value has been estimated at $1{\cdot}591 \times 10^{-19}$ coulomb, a *coulomb*, of course, being the quantity of electricity which corresponds to a flow of one ampere for one second. The ratio of e (the charge of the electron) to m (its mass) has been found to be $1{\cdot}77 \times 10^{7}$ in electromagnetic units, and this value of e/m will be found useful in calculations.

Electron Theory.—An atom of an element is supposed to consist of a positive nucleus, or core, around which revolve a number of electrons. Nothing, or little, is known of the positive core, although its mass is very great compared to that of the electron. The chemical nature of an atom appears to depend on the number and arrangement of its electrons. Thus the difference between gold and lead is probably that in one case there are more electrons than in the other, and their arrangement is also probably different. If we could alter the number of the electrons in an atom we would very likely be able to change lead into gold, or *vice versâ*. So far, no physical forces at our disposal have been able to affect in

* See Thomson's book "Conduction of Electricity through Gases," and his book "The Corpuscular Theory of Matter" (Constable & Co.).

† This name was given to the electrical charge carried by one hydrogen atom by G. Johnstone Stoney in 1891.

the slightest degree the structure of the atom. We have, nevertheless, in radio-active metals, examples of atoms emitting some of their electrons and therefore changing their character. We cannot, however, accelerate the process, which is exceedingly slow. It has been estimated that it would take 50,000 years for a piece of radium (a radio-active element) to change to an element of slightly different characteristics.

In addition to the electrons which form part of the essential structure of atoms, we have another type which may be detached from the atom. These electrons, which vary in number according to the elements to which they are attached, give the atom some of its physical properties. Normally the atom possesses no electrical charge, the positive nucleus and the electrons neutralising each other. If any of the detachable electrons be taken away from the atom, the latter becomes a positively charged *ion* and exhibits all the properties of an electrically charged body. If additional electrons be placed on a normally uncharged atom, the latter becomes what is called a *negative ion* and possesses the characteristics of a negatively charged body. The difference, then, between a positively charged body and one negatively charged is that the former has a deficiency of electrons while the latter has an excess.

Frequently, when two substances, such as ebonite and wool, are rubbed together, one becomes negatively charged while the other receives an equal positive charge. This is explained by saying that electrons are taken away from the wool, making it positive, and placed on the ebonite, thereby giving the latter a negative charge.

If a certain body possesses more detachable electrons than another, the first is said to be *at a higher negative potential* than the second. If the two bodies are close to each other in air and their potential difference is made very great, the electrons on the negatively charged body will endeavour to cross over to the body which is deficient of electrons. A *spark* may result, which is the visible result of the passage of the electrons which, through friction and impact, render the air between the gap white hot and therefore luminous. This passage of electrons constitutes an *electric current*, which may be considered to be a flow of negative particles of electricity from negative to positive. This appears to be in contradiction to the convention, decided on before electrons were discovered,

that electricity always flows from positive to negative. This should, however, give no difficulty when understood. The author, throughout this volume, when speaking of an electric current flowing in a certain direction, will be referring to the direction in which the electrons are flowing.

If two bodies at different potential be connected by a metal wire, electrons will flow from the point of high negative potential to the point of low negative potential.* If glass were the connecting medium no current would normally flow. The metal is said to be a *conductor* and the glass an *insulator*. The difference between the two is that in the cases of conductors the detachable electrons are more or less free to move about from atom to atom, while in the case of insulators they are bound up with their atoms. The former type are termed *free electrons*. It has been estimated that there are about 10^{22} free electrons in a cubic centimetre of cold metal. Conductors of *high resistance* possess much fewer free electrons, while insulators possess none, or very few. As has been previously stated, if $1{\cdot}591 \times 10^{19}$ of these free electrons pass a certain point on a conductor in one second, the strength of the current is one ampere. The current is proportional to the rate of flow of the electrons.

Emission of Electrons from Heated Filaments.—Having digressed a little to discuss the elementary facts concerning electrons, we can now return to the important question of the factors governing the rate of electron emission from an incandescent filament. The factors are :—

(*a*) The surface area of the heated filament.
(*b*) Its temperature.
(*c*) The substance of which it is composed.
(*d*) The nature and pressure of the gas in which the filament is heated.

(*a*) The number of electrons emitted per second is, as would have been expected, proportional to the area of the surface heated. A filament twice as long as another will emit twice the number of electrons in a given time, provided it is at the same temperature.

(*b*) The temperature of the filament is a very important

* The words *higher potential*, as usually used, refer to higher *positive* potential. By higher *negative* potential a preponderance of electrons is implied.

governing factor. At low temperatures no electrons whatever are emitted. As the filament becomes red hot (at about 1000° C.) a very small number of electrons is emitted, which increases very rapidly as the filament is still further heated. The maximum thermionic currents are obtained just before the filament melts. It may be noted that the melting-point of tungsten is 3270° C., while that of platinum is 1755° C. In practice, the filament is heated by passing an electric current through it. In Fig. 1 is given a curve which shows how the rate of emission of electrons from tungsten measured in milliamperes per square centimetre area of filament, varies with the temperature to which the filament is raised.

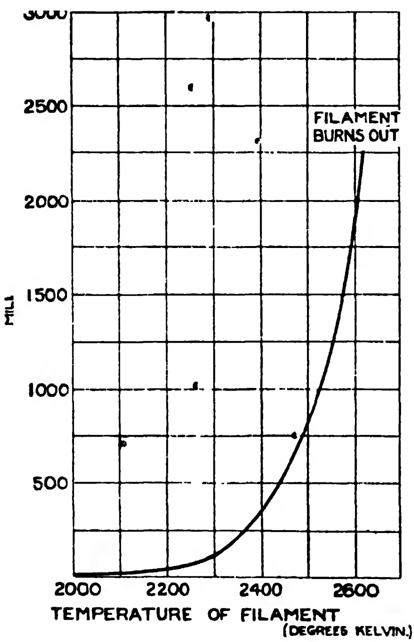


FIG. 1.

(c) Carbon filaments were the first to be used, but the thermionic currents obtained are not so great as those which are emitted from tungsten and tantalum. The latter can, moreover, be raised to very high temperatures, at which the rate of emission is great. Carbon, on the other hand, is much more easily volatilised. Platinum has been used but gives even smaller currents than carbon. The best radiators of electrons are the alkaline earths. Filaments coated with lime or barium oxide, when heated, give strong emanations of electrons. The disadvantage of such coated filaments is that they cannot conveniently be heated to high temperatures but readily burn out or become disintegrated. In 1903 and 1904, A. Wehnelt investigated the thermionic emission from platinum wires

coated with oxides of calcium, barium or strontium. G. Owen has studied the emission of electrons from the glower of a Nernst lamp which consists of oxides of rare earths.* It is an important point to note that a slight addition of thoria to tungsten very greatly improves the emission from this metal, although the slight irregularities caused thereby make filaments of this composition unsuitable for the receiving valves to be discussed.

(*d*) Another factor which affects the emission of electrons from heated filaments is the nature and pressure of the gas surrounding the filament. The presence of oxygen or any gas containing oxygen, even when at as low a pressure as 1/1,000,000 mm. of mercury, will cause the electron emission to be much less than that obtained when the vacuum is almost perfect. Hydrogen and a few other inert gases appear to have the opposite effect. H. A. Wilson has stated that the hydrogen occluded (*i.e.* absorbed on the surface) by platinum has an important bearing on the emission of electrons from that metal. If this hydrogen, which platinum has the peculiar property of retaining on its surface, be driven off by boiling the filament in nitric acid, the emission is reduced to 1/250,000 of its previous value. Irving Langmuir, however, has found that the presence of hydrogen greatly decreases the emission from a tungsten filament.

From the above remarks it will be seen that for a given bulb and filament and for a constant pressure of any gas that may be in the bulb, the *rate of electron emission is solely dependent on the temperature of the filament* and on no other factor.

The actual rate of emission as given in 1901 by O. W. Richardson,† the first serious investigator of the subject, is :—

$$I = aT^{\frac{1}{2}}\epsilon^{\frac{-b}{T}}$$

where I = electron emission per square cm. of the hot body,
T = absolute temperature of the body,
a and b = constants.
ϵ = 2·718 (base of Napierian logarithms).

* See G. Owen, *Phil. Mag.*, viii. p. 230 (1904), "On the Discharge of Electricity from a Nernst Filament."

† *Proc. Camb. Phil. Soc.*, **2,** 285 (1901) ; *Phil. Trans. Roy. Soc.*, A , 201 (1903)

The following values have been given for the constants a and b:—

For carbon : $a=10^{34}$, $b=9{\cdot}8\times10^4$ (J. J. Thomson)
„ platinum : $a=7{\cdot}5\times10^{25}$, $b=4{\cdot}93\times10^4$ „ „
„ tungsten : $a=2{\cdot}36\times10^{10}$, $b=5{\cdot}26\times10^4$ (I. Langmuir)

It will be seen that for lower temperatures the electron emission is greatest from carbon, and that stronger emission from tungsten is obtained because it can be heated to as high a temperature as 2600° Kelvin (= 2600° *absolute temperature.* The absolute temperature is obtainable by adding 273° to the centigrade temperature).

Thermionic Currents.—When a filament is heated, the free electrons within vibrate at a rate which rapidly increases as the temperature of the filament is raised. Since the electron has both mass and velocity, it is capable of doing work. In other words, it possesses *kinetic energy* which is equal to half its mass times the square of its velocity. As the velocity of the electron within the filament increases rapidly with the temperature of the latter, the kinetic energy becomes so great that the electron oozes out from the filament at a speed of about 15 cms. per sec., overcoming the force which normally retains the electron within the filament. Since the nucleus of an atom is positive, it attracts its parasitic negative electrons, which therefore require to attain a certain speed before they can leave their parent atom. The electrons, while endeavouring to escape, continually take part in collisions, so that it is little wonder that when they leave the surface of the filament their velocities vary, as do also their orbits of flight. In general, their orbits are parabolas; when they reach the surface of the filament they meet with opposition from the molecules of the low-pressure gas within the glass bulb, and when their energy is exhausted, they return again to the filament and are reabsorbed, just as a stone when thrown into the air returns again to earth.

When a filament is heated by means of an electric current a magnetic field is established round it in the form of rings. This magnetic field naturally affects to a certain extent the path of electrons as they are emitted from the filament.

Space Charge.—The electron, as it emerges from the filament, has to overcome, not only the attractive force of the filament and the resistance of the attenuated gas (the greater the pressure of the gas the greater the resistance), but also

the repulsion exercised by the cloud of electrons moving about at a greater distance from the filament than its own. This cloud of electrons, consisting as it does of thousands of particles of negative electricity, is an actual negative charge in space and is therefore generally termed a *space charge*. As our electron travels further away from the filament, the number of electrons in front of it decreases and the repulsion of the space charge consequently becomes less. Moreover, the electron is now helped on its way by the space charge *behind* it, which consists of electrons which have just emerged from the filament. It is important to note these forces acting on the electron, because later, when we discuss the action of the vacuum valve, we will see that they account for several curious phenomena.

The space charge was apparently first explained by C. D. Child, in 1911.*

Effect of Introduction of Plate.—Suppose that we have a very highly exhausted glass bulb containing a straight tungsten filament heated to incandescence by means of, say, a four-volt accumulator. Electrons will be emitted. Some will go to the inside of the glass bulb and charge it negatively. This negative charge will prevent further electrons from leaving the neighbourhood of the filament. It will *not*, it is important to notice, affect the rate of emission, which (other things remaining the same) is solely dependent on the temperature of the filament. The final result is that the electrons all return again to the filament.

Now let us imagine that we have introduced into the bulb a thin unconnected metallic plate about 2 cms. distant from the filament. The plate, of course, has no charge and it is therefore at a higher positive potential, relatively, than most parts of the bulb. Electrons, which always tend to flow from a point of low positive potential to one of high potential, will therefore accumulate on the plate and charge it negatively. This process continues until the plate is so negative that it begins to repel electrons which anticipated going to it.

Having considered an isolated plate, let us now suppose that we give the plate an electrostatic positive charge. Since the plate is positive it has had electrons taken away from it, and it naturally desires to make good the deficiency by attracting to itself the electrons which are being emitted by

* See *Physical Review*, xxxii. p. 489 (1911).

the filament. In other words, there is an electric field existing between plate and filament. Lines of force leave the plate and end at the filament. It is along these lines that a unit positive charge of electricity (the unit formerly used) would travel. Electrons, being negative, would travel along the same lines but in the *opposite* direction or sense. All this is equivalent to saying that the positive plate will attract negative electrons to it. This attractive force will depend upon the potential of the plate relative to the filament. The work done on the electron by the electric field between our two points is equal to its charge multiplied by the difference of potential between plate and filament. This work appears as the kinetic energy possessed by the electron as it reaches the plate. This energy is half the mass of the electron times its final velocity squared. We therefore have—

$$\tfrac{1}{2}mv^2 = Ve$$

where m — mass of electron.

e — charge ,,

v — final speed of electron

V — potential difference between plate and filament

From this we get—

$$v = \sqrt{\left(2V\frac{e}{m}\right)}$$

The ratio $\frac{e}{m}$ has been found by various methods to equal $1{\cdot}77 \times 10^7$, when e is measured in electromagnetic units and m in grammes. We see then that the electron attains the following velocities for the plate potentials given:—

PLATE VOLTAGE.	ELECTRON VELOCITY.
1 v.	6,000 cms. per sec.
100 v	60,000 ,,
10,000 v.	600,000 ,,

We see from this that the electron strikes the plate with considerable force and if there are sufficient electrons they will, by their bombardment, increase the temperature of the plate. For a similar reason, if a metal target is fired at by a machine-gun the rain of bullets will render it warm. During some experiments, the author found that a bombardment of 6×10^{17} electrons per second travelling at about 120,000 cms.

per second (or 45 miles per minute), was sufficient to make red-hot a metal plate of 3 sq. cms. area and 0·008 in. thickness.

A number of electrons bounce off the plate, or are reflected by it, but return and are absorbed by it. Under some conditions the electron bombardment liberates a number of *secondary* electrons attached to the atoms of the plate. These extra electrons, unless specially collected, are also reabsorbed by the plate.

The flow of electrons between the filament and our isolated positively charged plate possesses magnetic qualities, just as in the case of a current flowing along a metallic conductor. The path of the electrons may be deflected by means of a powerful electromagnet, although this is not very simply demonstrated, since a stream of electrons is absolutely invisible.

It may also be mentioned here that the attraction of the plate causes a strain on the filament itself. If the plate is at a sufficiently high voltage, it may even break the filament. If the plate, however, be made in the form of a cylinder surrounding the straight filament, there is in the ideal case no strain on the latter in any one particular direction.

Maintenance of Constant Potential on the Plate.—We have simply imagined, so far, the conditions existing when the plate is isolated. After attracting electrons for a short time, the plate loses some of its positive charge. Finally, the electrons completely neutralise the charge and then begin to charge it to a negative potential. If we desire to maintain the flow of electrons from filament to plate we will require to maintain the latter at a constant positive potential with respect to the filament or to a portion of the filament. We can do this by connecting the positive side of the filament battery to the plate, or by connecting a battery across plate and filament. We frequently term the plate the *anode*, or positive electrode, and the filament the *cathode*, or negative electrode.

Potential Gradient along Filament.—Since the filaments of valves are nearly always heated by means of a current, there is always a *potential gradient* along the filament, although its decided importance in practice is not generally recognised or understood by students. They frequently fail to understand why it makes a difference sometimes when an accumulator is incorrectly connected across the filament of a valve. Fig. 2 will help to make the matter clear. The thin line AE represents a filament of even diameter heated to

incandescence by an accumulator H. The voltage across the filament is 4 volts, A being the negative and E the positive end. It is most convenient, and the principle will be adopted throughout this volume, to consider the end A as having a potential of zero volts. The potential of E will therefore be +4 volts. The potential of C, the midway point on the filament, will have a potential of +2 volts. At the quarter-way point B the potential is +1 volt, and at the three-quarter-way point D is +3 volts.

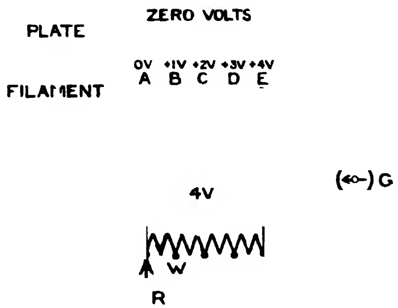


FIG. 2.—Showing potential drop across the filament of a valve.

In Fig. 2 we have also a resistance VZ, preferably having a high value, and a sliding contact R, shown as an arrow-head. Between the plate, shown as a thick line, and the point R is a sensitive galvanometer G.

The potential of V will be zero volts, that of Z will be +4 volts, that of X will be +2 volts, and the potentials of the quarter and three-quarter-way points W and Y will be +1 volt and +3 volts respectively. Intermediate potentials may be obtained by sliding R along VZ.

Let us first place R on V. Since the plate is connected to R, its potential will be zero. It is at the same voltage as the point A. It will therefore be at a potential 1 volt lower than B, 2 volts lower than C, 3 volts lower than D, and 4 volts lower than E. There will therefore be no tendency* for electrons to flow to the plate from *any* point of the filament, since the plate is completely negative to all parts of the filament. Let us now place R on W. The plate will now have a potential of +1 volt. It will therefore be at a potential 1 volt higher than A, 1 volt lower than C, 2 volts lower than D, and 3 volts lower than E. Since the plate is positive to the portion AB of the filament electrons from this portion

* In practice a *very* small electron current passes to the plate and round *via* G to R, when the filament is heated to a high temperature or the plate is close to AB. This is because electrons are *forced* on to the plate by their velocity. Later, the reader will find that in bulbs containing gas a very small current is liable to flow in the *opposite* direction, due to the plate attracting positive ions

will flow continuously to the plate and round the *plate circuit* GR, producing a deflection in the galvanometer G. These conditions are shown in Fig. 3. More electrons are drawn from the "A" end of AB. since the plate is at a higher potential to that end than the "B" end. No electrons are drawn from the actual point B, since the potentials of B and the plate are the same, namely +1 volt. No electrons, of course, are drawn from the part of the filament B to E, since the plate is *relatively* negative to that portion. The actual current flowing from the filament to the plate, usually called the *thermionic current*, is only a fraction of the actual electron emission from AB. It would take a very much stronger force than +1 volt on the plate to draw up all the electrons emitted from AB.

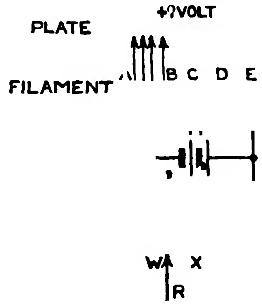


Fig. 3.—Showing the plate at a potential of + 1 volt.

If the slider R be adjusted to the point X, the plate will have a potential of +2 volts and will draw up electrons from the portion of the filament A to C, since it is at a relatively higher voltage. No electrons, however, will flow from the portion C to E, since the plate, being relatively negative to CE, repels them. These conditions are shown in Fig. 4. The thermionic current, as registered by G, has increased.

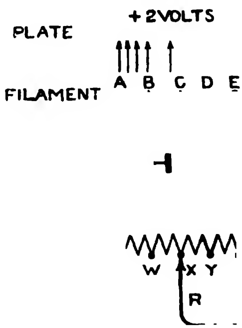


Fig. 4.—Showing the plate drawing electrons from one half of the filament.

Similarly, if R is at Y, the plate will draw up electrons from that portion of the filament which is at a lower potential than itself, namely, the part between A and D. The current through G, which is the equivalent of the current between filament and plate, increases, as shown in Fig. 5.

Lastly, if R be placed at Z, or in other words if the plate be connected directly to the positive end of the filament, the plate will be at a higher potential than any point on the filament, and will therefore attract electrons from *every* point. The dotted lines of Fig. 6 show the electron flow and illustrate

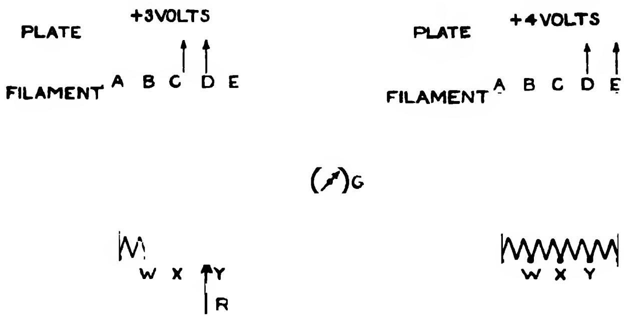


FIG. 5.—Showing the plate at a potential of + 3 volts.

FIG. 6.—The plate drawing electrons from every part of the filament.

how it is densest towards the negative side of the filament. The galvanometer G will register a still higher thermionic current, but the latter will still be very small and of the order of 0·1 milliampere. As R has been moved along VZ, this current has rapidly increased, partly because a greater portion of the filament has come under the influence of the plate, and partly because the attractive force, represented by the plate potential, has also increased.

From the above considerations we see that—

(1) If an electrode within a vacuum be connected directly to the negative end of the filament, there will be no tendency for an electron flow to be established.

(2) If the electrode be connected directly to the positive end of the filament electrons will flow from every part of the filament to it, since it is at a higher potential than the filament. Most of the electron current will come from the negative end of the filament, since it is there that the potential difference between electrode and filament is greatest. The potential of the electrode will be positive, and equal to the E.M.F. across the filament.

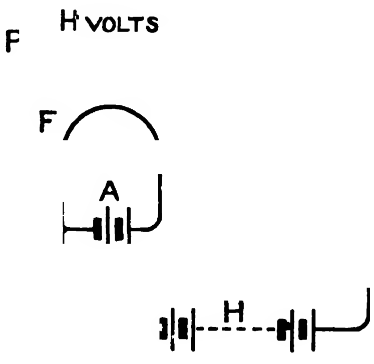
(3) If the lighting accumulator be shunted by a resistance which has a variable contact sliding along it, and the electrode

be connected to the sliding contact, the potential of the former may be varied between zero and a positive value equal to the E.M.F. of the lighting battery. The electron flow to the electrode will gradually increase as the sliding contact is moved towards the positive end of the resistance.

Avoidance of Potential Gradient along Filament.—The potential gradient along a filament is always a complication, although practical advantage is often taken of it. It becomes a serious factor when the voltage across the filament is, say, 30 volts, as it may be in the case of a large valve. To avoid the effect, the Marconi Company and H. J. Round have suggested, in British Patent 6,476/1915, using a platinum tube coated with lime and heated to incandescence by means of filaments passing through the centre of it without touching it. The General Electric Company have proposed an arrangement which is shown in Fig. 17, and explained later. By means of the first arrangement the filament may be made neutral with regard to the electrode. The Marconi device, though experimentally successful, has been of no commercial value.

Methods of applying Potential to Electrodes.—One method of applying a variable potential to an electrode has been given in Fig. 2. This potential, however, *will always be positive* and is never greater than the E.M.F. of the lighting accumulator. We frequently require the electrode to be at a much *higher* potential and sometimes at a *negative* potential. There are one or two slightly different methods of effecting this.

(*a*) In Fig. 7 a battery H is included in the electrode circuit. If the electrode be the plate of a valve, this battery is usually termed a *plate battery*, and sometimes a *high-tension* battery, although this latter term is not usually a correct one. A battery of 100 volts, composed of dry cells in series, variable by means of ten-volt tappings, will be a suitable size of plate battery for



7. Usual method of applying a potential to an electrode.

use in plate circuits, although much smaller batteries may be used with some valves.

For some purposes it may be required to place a negative voltage on the electrode. This can be accomplished by

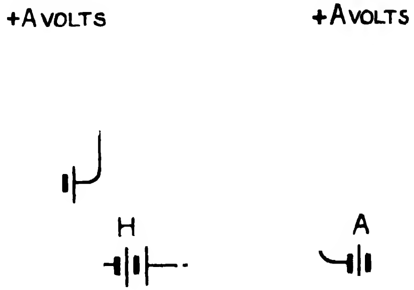


FIG. 8.—Two methods of giving the plate a potential equal to the E M F of the filament battery.

reversing H and connecting its negative side to the electrode and its positive side to the negative end of the accumulator A.

NOTE.—It will be seen that the battery H is connected to the *negative* side of the four-volt accumulator A. If we desired to give the electrode a positive potential of +4 volts we would connect a four-volt battery as shown in the left-hand circuit of Fig. 8. This, it will be seen, may be accomplished *without* the cells H, by connecting the electrode directly to the *positive* side of A as shown in the right-hand circuit. Similarly, if we desire to give the electrode P a potential of +10 volts, instead of connecting a ten-volt battery with its negative to the negative of the accumulator (Fig. 7), we may use a *six-volt* battery with its positive side connected to the *positive* of the accumulator, as shown in Fig. 9. If the accumulator voltage were 10 volts and the potential required on the electrode were 100 volts we would only need a battery of 90 volts provided we connected its negative side

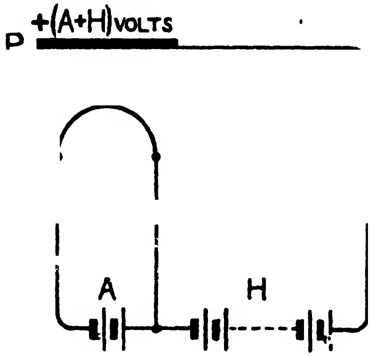


FIG. 9.—Economical method of applying a positive potential to an electrode.

to the positive of the accumulator. We therefore effect an *economy* by using such an arrangement. When the voltage of the accumulator is small compared to the voltage to be placed on the electrode, the economy is, of course, negligible. If, however, we had 30 volts across the filament, as may be the case in large bulbs, 30 volts of the battery H would be unnecessarily wasted if we used the connections of Fig. 7. By using the Fig. 9 connections we would save that 30 volts.

If our electrode is to be given a *negative* voltage, we obviously connect the positive side of our battery H to the negative of the accumulator. Fig. 10 shows that if we mak

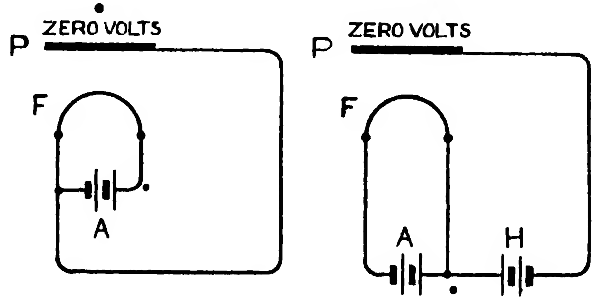


FIG. 10.—Showing the effect of connecting the electrode to different sides of the accumulator.

our connection to the *positive* of the accumulator we would require four volts in opposition merely to bring the potential of our electrode to zero.

To avoid any confusion, the author advocates connecting any electrode batteries to the negative side of the accumulator, as shown in Fig. 7. This arrangement will be shown in most of the following diagrams of valve circuits. A theoretical advantage of doing this is that any change in the voltage of the accumulator will not cause a change in the potential of the electrode, according to our agreed convention. For practical circuits, however, the negative of the plate battery may invariably be connected to the positive side of the filament battery.

(*b*) To obtain a fine adjustment of potential on an electrode,* we require a *potentiometer* or potential divider. Fig. 11

* Usually applied to the auxiliary electrode (or *grid*) of a valve

shows a resistance AE of, say, 400 ohms or more, shunted by a battery of dry cells H of, perhaps, 10 volts, and possessing a sliding contact P. The point E will be at a potential 10 volts higher than A, since the former is connected to the positive of the battery H. If the sliding contact P be placed on C, the potential of the electrode G will be +5 volts. If placed at A it will be zero, if at B it will be +2·5 volts if at D it will be +7·5 volts. Intermediate potentials are obtained by sliding P along AE. If the range of potentials is a little too small, the voltage of the battery H may be increased. This can only be done to a certain point, because the current through AE may become excessive and injure the resistance (which will usually carry about 0·3 ampere), and the battery H may also be injured or, at least "run down." It is therefore preferable to connect another battery in the electrode circuit at Q, as shown by the dotted lines at the right of Fig. 11. This arrangement should be used if it is desired, for example, to have a finely variable voltage on the plate of a valve.

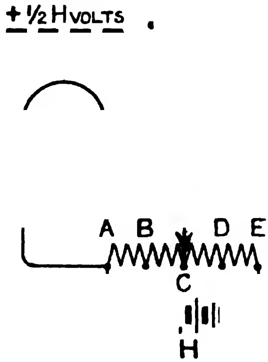


FIG. 11.—Use of a potentiometer to vary the potential of an electrode.

Fig. 11 shows the electrode as having a variable *positive* potential. If we require to give it a variable *negative* potential we have only to reverse the connections of the potentiometer battery H. This may be inconvenient, and one of the arrangements described below may be more suitable when either a positive *or* negative potential on an electrode is required.

A practical point worth noting is that the voltage of the potentiometer battery H should not be unnecessarily high, because, if it is, the slightest movement of the sliding contact P will cause a considerable change of potential on the electrode, and delicate adjustment will be correspondingly more difficult.

(*c*) Fig. 12 shows a potential-divider which allows for both positive and negative variable potentials to be placed on the

electrode. The connection from the filament is taken this time to the point X, halfway along the potentiometer battery H. The total E.M.F. of H is shown as 8 volts. The potential of C is now zero. The potential of A is −4 volts and E +4 volts; the potential of B is −2 volts and of D +2 volts. The arrangement therefore gives a variation of potential from −4 volts to +4 volts. If the range desired were from −12 volts to +4 volts, the arrangement of Fig. 13 would be suitable. The connection X is now made as shown. The

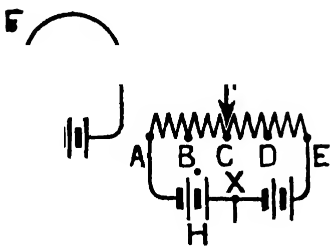


FIG. 12.—Use of a potential divider to obtain either positive or negative potentials on the electrode.

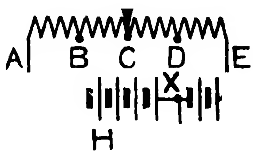


FIG. 13.—Potentiometer arrangement to obtain special range of voltages.

potential of D is zero, of E +4 volts, of C −4 volts, of B −8 volts, of A −12 volts.

No battery voltage whatever is wasted, and the arrangement would adapt itself to the use of an ordinary graphite rod, such as that of an ordinary pencil, for the resistance AE. It is, however, a little complicated on account of the separate tapping from the battery.

(*d*) Fig. 14 shows a very useful potentiometer for general use in valve circuits. It consists of a resistance AE having a tapping taken from its halfway point. The potential of the electrode when the sliding contact P is at C is zero. The potential at E is negative and is half the E.M.F. of the battery. In this case, it is −6 volts; the potential at D is −3 volts, at B +3 volts and at A it is +6 volts. The range is therefore from −6 volts to +6 volts. If this is not

enough, the E.M.F. of the potentiometer battery may be increased.

If a *special* range is desired, the connection may be taken from another point along the resistance AE. Fig. 15 provides a range of from —30 volts to +10 volts. The distance BE is made three times AB. The resistance AE should, of course, be great for such a voltage to avoid too heavy a current. Otherwise, the actual resistance of AE is immaterial.

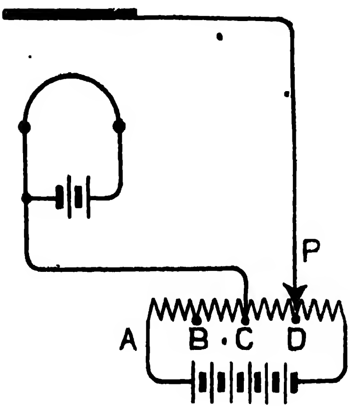


FIG. 14.—Usual form of potentiometer.

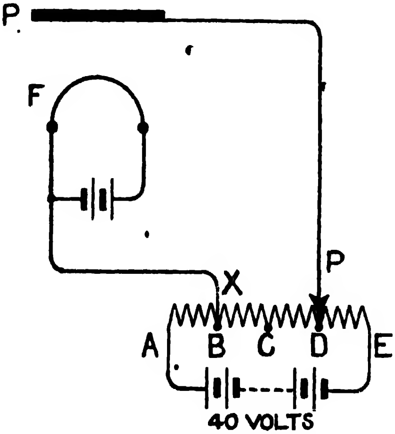


FIG. 15. Potentiometer arrangement for special range of voltages.

Method of varying Filament Temperature.—The temperature of the filament, and consequently the rate of electron emission, may be varied by including in the filament circuit a variable resistance (of about 7 ohms in the case of the average small valve). This *rheostat* enables us to control the filament current, and should, for preference, be *smoothly* variable. A multiple-stud switch may be used, but a radial arm moving along coils of resistance wire arranged in the form of a circle is much better.

Variation of Temperature along Filaments.—Normally, the temperature along a filament is uniform, except at the ends where cooling takes place. When, however, there is a plate current, this current adds itself to the filament current and causes one half of the filament to be hotter than the other.

This may be shown by arranging a circuit similar to the one shown in Fig. 16. In the plate circuit of the valve is a plate battery H, and a switch. The plate circuit may be completed by closing the switch. Between the negative end B of the filament and the accumulator A is connected an ammeter G_1. Between C and A is another ammeter G_2.

If we leave the switch *open*, we will see that the filament current readings in G_1 and G_2 are the same. Suppose the filament current, which is flowing, according to the electron theory, in the direction of the arrowheads, be 1 ampere as registered by both ammeters. On closing the switch it will be noticed that the reading in G_1 will increase above 1 ampere, while that of G_2 will decrease below that value.

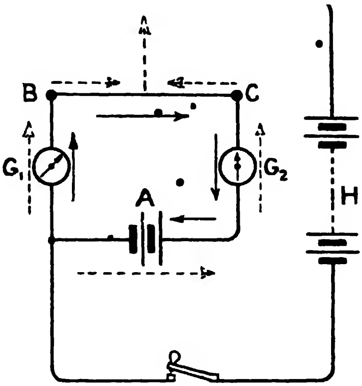


FIG. 16. Effect of plate current on filament temperature.

The phenomena is explained by the existence of an electron current in the plate circuit which flows round by H and the switch and divides at the connection to the filament. Part of the electron current flows *via* G_1, B, the filament, and thence to the plate as shown by the dotted-line arrow-heads. It therefore *reinforces* the electron current from the lighting accumulator which is flowing in the same direction. Another portion of the thermionic current flows *via* A, G_2, C, the filament, and thence to the plate. This current *opposes* the existing electron current in the filament circuit and causes a reduction in the current passing through G_2. The result is that the negative half of a filament is always hotter than the positive half, no matter to which side of the accumulator the negative of the plate battery may be connected. In practice, this peculiar effect is of no importance except when the temperature of the filament is already near melting-point and the plate current great. Under such conditions, the filament is liable to burn out when the plate circuit is completed.

The General Electric Company (of U.S.A.) and W. C. White have devised the arrangement shown in Fig. 17. The filament is heated by alternating current drawn from a transformer, T. The connection from an electrode in the valve is taken to the middle point X of the secondary winding. The bad effects due to the phenomenon described above are decreased by this system.

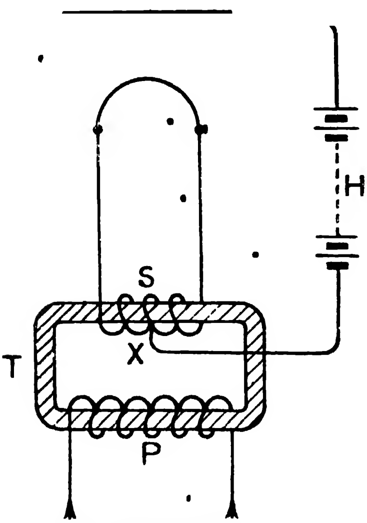


FIG. 17.—W. C. White's method of making connection to a filament heated by alternating current.

When the filament is heated by current from an accumulator, connection may be taken from the middle point of the accumulator. By doing this the thermionic plate current acts, for one half of the filament, in series with only half the E.M.F. of the accumulator.

Effect of Gas in a Valve.—When thermionic currents were first investigated, it was thought that they were possibly produced through some chemical action between the incandescent filament and the surrounding gas. Since those days, however, much higher degrees of exhaustion have been obtained and vacua produced of as low a pressure as 10^{-9} millimetre of mercury. Irving Langmuir, the originator of the "*hard*" (*i.e.* of very low pressure) vacuum valve,* has shown that thermionic currents are obtainable from incandescent filaments in almost pure vacua. He explains that very weak currents only were obtained previously because the plate voltages were not high enough.

When the "vacuum" of a valve contains small quantities of gas, the thermionic currents obtained by placing a positive voltage on the plate are very much greater than those obtained

* Fleming considered the use of very hard valves but high degrees of exhaustion were not possible at the time. The hard valve appears to have been rather a practical improvement than a new invention.

when the gas is entirely absent, provided *ionisation* takes place.* The reason for this is not because the actual rate of electron *emission* is affected, but because the electrons, on their journey to the plate, collide with the molecules of the gas and, by the violence of the collision, shake out additional free electrons which also join the main stream. The greater the voltage on the plate, the greater will be the speed of the original electrons, and therefore a larger number of free electrons will be liberated from the molecules of the gas. This increase of the normal plate current due to the presence of gas is especially marked when the values of filament current and plate voltage are high.

When the *primary* or original electron attains a velocity sufficiently high to break off electrons from the gas molecule, it will leave the latter positively charged. The gas molecule has been *ionised* and is now a *positive ion*. This process of *ionisation by collision* is generally accompanied by a bluish glow which pervades the space between filament and plate and sometimes fills the entire bulb. The glow is absent at certain pressures of gas, although ultra-violet rays are almost invariably emitted. The positive ions thus formed flow from the plate, which is positive and repels them, to the filament, which is the point of lowest potential in the bulb. The mass of these ions is very much greater than in the case of electrons and the ionic bombardment of the filament rapidly disintegrates the latter.† It has also the effect of shaking out from the filament a further quantity of electrons. These electrons have been termed Delta rays. In some circumstances, however, the positive ions form a layer round the filament through which the electrons find it difficult to pass. Other causes of ionisation in the bulb or *vacuum tube* include the effect of the high temperature of the filament on the gas in the immediate vicinity, and the ionisation produced by the collision of the *positive* ions with the gas molecules. A certain amount of ionisation is also produced, probably by the contact of gas molecules with the highly charged positive plate.

The positive ions, however they may have been formed, have one great effect. They tend to neutralise the repulsion exercised on newly emitted electrons by the cloud of negative

* If ionisation is absent, the electron current to the plate usually increases as the vacuum becomes more perfect.

† This disintegration may also be due to some obscure chemical action.

electrons travelling to the plate. The positive ions, while moving too quickly actually to *combine* with the electron cloud and neutralise it in that way, constitute a *positive space charge* which tends to *attract* newly emitted electrons. The screening effect of the electron space charge is therefore greatly minimised, and the number of electrons able to reach the plate is very much increased.

From the above considerations we see that a *soft* valve, that is, one which contains gas, will conduct much more readily than a *hard* valve. To obtain the same thermionic current, it is necessary to use a very much higher plate voltage in the case of a hard valve. It has been found that 25 volts on the plate of a certain valve containing mercury vapour at a pressure of 10^{-5} mm. gave a current of 0·1 ampere. When the pressure was reduced to 10^{-7} the plate voltage required to obtain the same current was about 200 volts. We may summarise the reasons for the increased current in the case of soft valves, as follows:

(*a*) Positive ions, chiefly produced by collision of high-velocity electrons with gas molecules, counteract the repulsion exercised by the negative space charge.

(*b*) The electrons liberated from the gas molecules go to swell the filament-plate electron current.

(*c*) The positive ions, on collision with gas molecules, liberate a number of electrons which join the main flow.

(*d*) The positive ions, on striking the filament, liberate a number of additional electrons, and doubtless increase its temperature.

(*e*) The high temperature of the filament ionises the gas which comes in contact with it, liberating electrons.

(*f*) Some of the gas molecules are charged positively through contact with the highly positive plate.

SIMPLE RECTIFYING ACTION OF THE VALVE.

Circuit to demonstrate Rectifying Action of the Valve.—The term *valve* was originally given to the vacuum bulb containing a heated filament and cold plate, because it was discovered that a flow of current through the device could take place in one direction, but not in another. The "Edison effect,"

demonstrated in 1884 by the great inventor, is, in the light of more recent discoveries, easily explained. We may demonstrate this valve action ourselves by connecting up the circuit shown in Fig. 18. When the positive side of H is connected to the plate, an electron current flows from F to P and round the plate circuit H and G, producing a deflection in the milliammeter G. If now we reverse the connections to H, no electron current will flow, and no deflection of G will be noticed. The valve is, therefore, said to possess *unilateral conductivity*, since it passes current in only one direction.

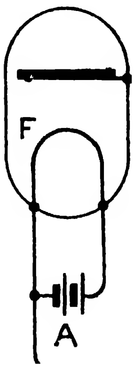


FIG. 18.—To demonstrate the rectifying action of a valve.

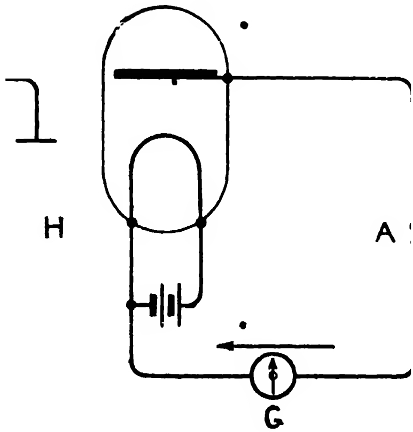


FIG. 19.—Circuit to demonstrate the unilateral conductivity of a valve.

If, in place of the battery H, we connect a source of alternating current to the valve we can use the latter as an arrangement for producing direct current (Fig. 19). This current, though direct, will be of an intermittent nature, since no current flows for the negative half-cycles of alternating current.

The Kenotron Rectifier.—The General Electric Co. (U.S.A.) have in recent years utilised the unilateral conductivity of a valve for producing direct currents from an alternating supply. They call these rectifiers Kenotrons (from the Greek *Kenos* = vacuum and *Tron* = an instrument). They are very hard vacuum tubes capable of rectifying alternating currents of as high a voltage as 50,000 volts with an efficiency of about 97 per cent. The vacuum is so perfect that when the filament is not heated no current passes through the valve in either

direction even up to potentials of 100,000 volts. Their size, of course, depends upon the amount of current they are to pass. If the latter is great, several kenotrons may be connected in parallel. Although hard valve rectifiers appear to have been largely developed by the General Electric Co. (U.S.A.), yet a great deal of work has been carried out by the Osram Lamp Works and the Edison Swan Electric Co. on the production of very hard rectifying valves for high-power work.

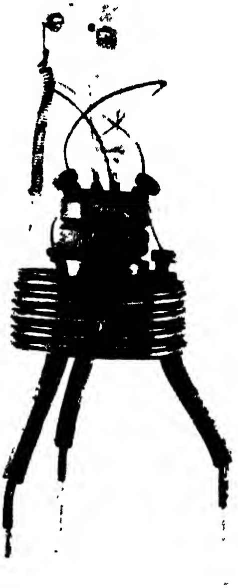


FIG. 20.—An early Fleming valve.

The Fleming Valve.—J. A. Fleming was the first to apply, in 1904, the rectifying properties of the valve to the reception of wireless signals,* and it is him we have to thank for opening up this very valuable field for research. His valve at first consisted of an ordinary carbon filament incandescent lamp, containing, in addition, a spiral of wire or metal plate. Fig. 20 shows one of the original valves used by Fleming in 1904. Later, he used a carbon filament surrounded by a metal *cylinder*. It is not proposed to give details of the Fleming valve, since it is hardly any longer in use as a detector.

Fig. 21 shows a very simple circuit in which a Fleming valve is used to rectify the very high-frequency oscillations taking place in a wireless receiving circuit, due to a distant transmitting

* J. A. Fleming, "Principles of Electric Wave Telegraphy and Telephony," 2nd edition, p. 476. Also British Patent 24850/04 (Nov. 16/04)

station. One end, the high-potential end, of the inductance L_2 is connected to the plate of the valve, while the other end is connected to the negative end of the filament. In the plate circuit is connected a pair of high-resistance wireless telephones T, shunted by a small condenser C_2. The rheostat R allows the filament current to be varied.

When a train of waves is received, the potential of the plate P becomes alternately positive and negative. This occurs,

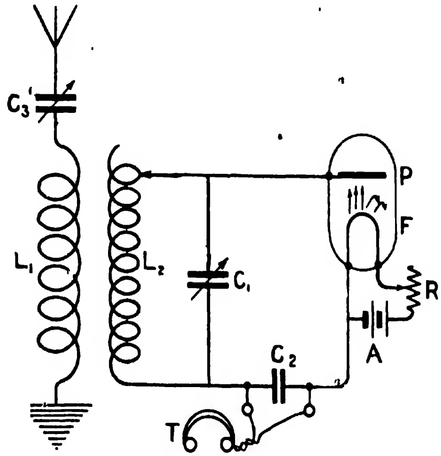


FIG. 21.—Simple Fleming valve circuit.

perhaps, at the rate of 500,000 times per second. When a positive half-cycle of alternating current gives the plate a positive charge, the potential of P becomes greater than the potential of the negative end of the filament. Electrons will therefore flow from a portion of the filament to the plate. This flow will continue round L_2 and T and back to the filament, so completing the circuit. There will be practically no delay in the establishment of this current, since the electrons in the valve are exceedingly mobile and possess a negligible inertia.

The next half-cycle gives the plate a negative potential, and P therefore does *not* attract electrons * and no electron current flows through the telephones T.

* In the case of the actual Fleming valve, which is soft, a very small current *in the opposite direction* flows through T when P is negative. This is due to the attraction to the plate of positive ions.

During a wave-train, the telephones T receive, perhaps, twenty very small pulses of unidirectional current. These follow too rapidly to be individually audible. It may be assumed that the small condenser C_2 stores up these small rectified currents and that it discharges periodically through the 'phones. However this may be, the resultant effect in T is that of one pulse of direct current for each wave-train, and this pulse produces an audible click. Dots and dashes sent by the transmitter will therefore produce short and long buzzes in the telephone receivers.

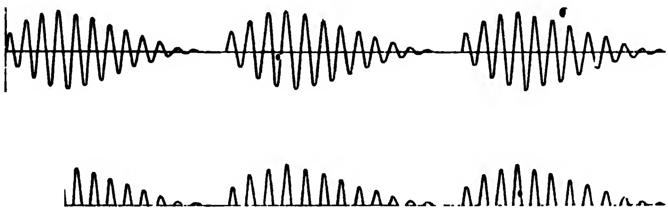


FIG. 22.—Graphical representation of the rectification of wave-trains by a valve.

Fig. 22 illustrates the complete process. In the first line we see the wave-trains, or rather oscillation-groups. In the second, the negative half-cycles are missing since they produce no electron current through the 'phones. The third line shows the movement of the telephone diaphragm which follows the *average* current of the high-frequency rectified pulses. These *average* pulses of direct current are termed low or *audio* frequency pulses. The original oscillations are of high or *radio* frequency.

THE CHARACTERISTICS OF THE TWO-ELECTRODE VALVE.

The Effect of Plate Voltage on Plate Current.—We have seen that if we increase the voltage of the plate of a valve we will

increase the plate current. Let us try and find out what exactly happens. If we connect up a circuit similar to that shown in Fig. 23 we can carry out a series of interesting and valuable experiments which will throw considerable light on the working of the simple two-electrode valve we have so far discussed. An ammeter G, reading up to about 2 amperes, is included in the filament circuit. A milliammeter G_1, reading up to about 10 milliamps., is included in the plate circuit. The value of the filament current may be varied by the rheostat R. The value of the plate potential is measured by a voltmeter V_1, and may be varied in steps of, say, ten volts by means of the plate battery H. If desired, the plate potential may be made a round number by the use of a potentiometer P in series with H.

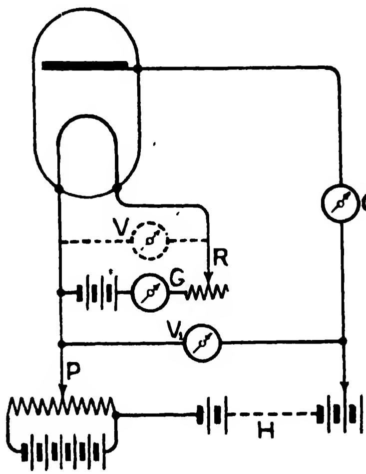


FIG. 23. Circuit for obtaining characteristic curves.

Our first investigation is to find out how the plate current varies as we increase the plate voltage from zero. We will assume our valve is perfectly "hard." For negative values of plate voltage there will, therefore, be no electron current registered by G_1. If G_1 be sufficiently delicate, an extremely small electron current may sometimes be detected even when the plate is at zero or even at a slightly negative potential. This is because some of the electrons of higher velocity *force* themselves on to the plate even though they are not wanted. Keeping our filament current constant at, say, 0·6 ampere (corresponding to 3·5 volts across the filament) we increase our plate voltage in steps and record our results in tabular form. An example of such results is given in Fig. 24. In this case the steps were regular.

In order to see more clearly what information we have obtained, we can plot our results on squared paper in the form of a curve, which is known as the *characteristic curve* of the

Filament current.	Plate voltage.	Plate current.
0·6 Amp.	0 Volts	0 Milliamp
,,	10 ,,	0·10 ,,
,,	20 ,,	0·30 ,,
,,	30 ,,	0·60 ,,
,,	40 ,,	1·05 ,,
,,	50 ,,	1·56 ,,
,,	60 ,,	1·96 ,,
,,	70 ,,	2·25 ,,
,,	80 ,,	2·47 ,,
,,	90 ,,	2·58 ,,
,,	100 ,,	2·63 ,,
,,	110 ,,	2·66 ,,
,,	120 ,,	2·68 ,,
,,	130 ,,	2·69 ,,
,,	140 ,,	2·70 ,,
,,	150 ,,	2·70 ,,

FIG. 24.

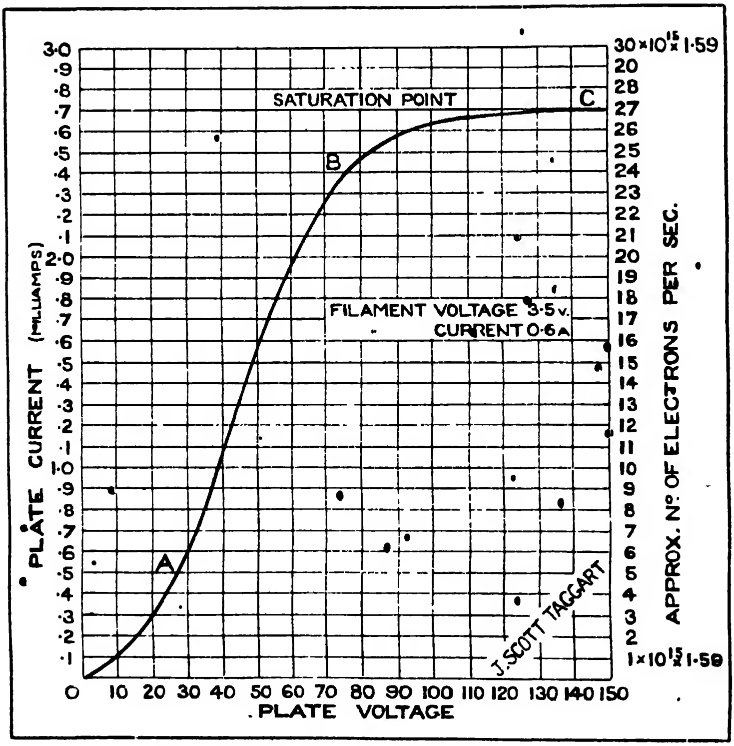


FIG. 25.—Variation of plate current with plate voltage.

valve connecting plate voltage and plate current. Fig. 25 shows the curve. Plate voltages are marked along the horizontal or " Y " axis, and plate currents are marked along the vertical or " X " axis.

We see from our curve that as we increase our plate voltage so do we increase our plate current. There are, however, one or two peculiarities about the curve. We notice, for example, that the plate current increases slowly at first and then more rapidly after the point A. Between A and B the curve is straight; in other words the plate current increases uniformly. After the point B, however, the plate current increases more and more slowly for equal increases of plate potential. This is shown by the bend of the curve between B and C. A point C is ultimately reached (at 140 volts), when a further increase of plate voltage produces practically no increase of plate current. This point is known as *saturation point*. Once saturation point is reached, a voltage on the plate ten times saturation voltage would produce practically no further increase in the plate current. This, of course, is quite different to the case of an ordinary conductor, such as a length of wire. The ordinary conductor obeys Ohm's Law, which states, *inter alia*, that the current in a conductor is proportional to the potential difference across it. Fig. 26 shows a voltage-current curve for a length of wire having a resistance of about 1·5 ohms. The " curve," which is symmetrical and rectilinear, extends in both directions. It makes no difference which way round the E.M.F. be applied. Most regular curves may be represented by

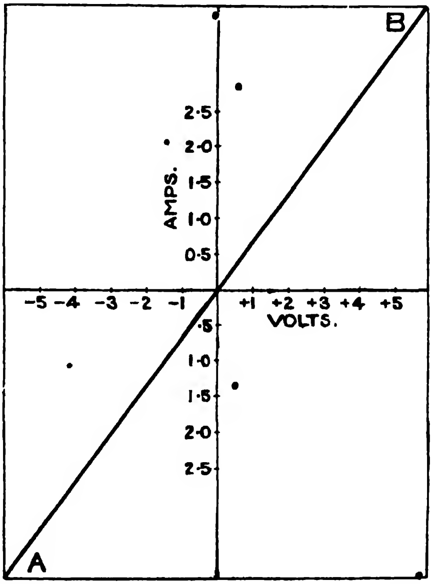


FIG. 26.—Voltage-current curve of an ordinary conductor of 1·5 ohms resistance.

an equation. The Fig. 26 curve will be seen to follow the equation

$$I = \frac{V}{R}$$

where I = current in amperes,
V = voltage across the conductor,
R = resistance of conductor in ohms.

It is much more difficult to find an equation for our Fig. 25 curve. Irving Langmuir, to whom we are largely indebted for the hard valve and who drew up laws concerning this type of tube, states * that for a given valve and given filament temperature, the plate current is proportional, not to the plate voltage, but to the *square root of the cube of the plate voltage.*

That is :

$$I = fV^{\frac{3}{2}}$$

where I = plate current,
f = a constant,
V = plate voltage.

It should be noted that this formula only applies to the portion of the curve between the *origin* O and the point B, just below saturation. It may be mentioned, incidentally, that if the "plate" (or, more correctly, the anode) be a metal cylinder of radius r surrounding a straight filament, the plate current

$$I = \frac{fV}{r}$$

That is to say, if we doubled the radius of the cylindrical anode, we would halve our anode current. If the cathode and anode were equipotential surfaces of infinite extent, the anode current would be inversely proportional to the square of the distance between them.

Explanation of the Bends in the Curve.—It will be seen from Fig. 25 that below A there is a distinct bend in the characteristic curve. The reason for this bend is usually attributed to the effect of the *space-charge* existing between the filament and the plate. This space charge has a repellent effect on the electrons emerging from the filament. It acts as a barrier

* Irving Langmuir, in a paper read before the Institute of Radio Engineers, April 7, 1915. Also published in the *General Electric Review*, May, 1915, and *Electrician*, May 21, 1915. See also British Patent 15788/14 (July 1/14), which is intended to cover hard valves.

through which the electron has to force its way. The positive potential of the plate tries to attract the electron and therefore opposes the effect of the negative field. The latter, however, is much nearer to the filament and therefore tends to keep down the electron flow from filament to plate. Many electrons, however, manage to come through the field and reach the plate, but not as many as there would have been had the space charge not existed. The result is that the curve is concave along its lower portion.

At the upper end of the curve we find a more important bend near *saturation point*. The reason for its existence may be explained as follows: The filament of the valve is only capable of emitting a certain number of electrons per second at a given temperature. The total amount of thermionic current which could be drawn from the filament under the Fig. 25 conditions was 2·7 milliamperes. Since about $1{\cdot}59 \times 10^{19}$ electrons per second are equivalent to 1 ampere, the electron emission from our filament may be taken as being $27 \times (1{\cdot}59 \times 10^{15})$ electrons per second. When the plate voltage is zero, practically all these $27 \times (1{\cdot}59 \times 10^{15})$ electrons return again to the filament. When the plate potential is +10 volts, $1{\cdot}0 \times (1{\cdot}59 \times 10^{15})$ electrons flow to the plate. The remaining $26 \times (1{\cdot}59 \times 10^{15})$ return again to the filament. The plate is now only capable of drawing up $1{\cdot}0 \times (1{\cdot}59 \times 10^{19})$ electrons per second. If we increase the plate potential to +30 volts, our plate current becomes 0·6 milliamp., that is $6 \times (1{\cdot}59 \times 10^{15})$ electrons are drawn to the plate and $21 \times (1{\cdot}59 \times 10^{15})$ return to the filament. The number of electrons per second drawn to the plate is given on the right-hand scale of Fig. 25. After we have reached the point B, the electron flow increases more slowly. There are always a number of electrons which show no inclination to go to the plate. They are generally those which are slowly emitted from the filament or those whose orbit is small. It is with great difficulty that they can be made to join in the main stream, and it requires, in our case, the same increase of plate voltage to draw up these last $3 \times (1{\cdot}59 \times 10^{15})$ electrons as it did to attract an additional $18 \times (1{\cdot}59 \times 10^{15})$ previously. Our curve, therefore, becomes convex and bends over to the right until it reaches the point C. The plate current now ceases to rise because the plate is now drawing $27 \times (1{\cdot}59 \times 10^{15})$ electrons per second, the total number actually emitted by the filament when the latter has a current of 0·6

D

ampere passing through it. It is therefore obvious that no matter how high a potential we place on the plate, we cannot draw up any more electrons than are actually emitted by the filament. The plate current of a hard valve, it must be remembered, is carried purely by the electrons emitted by the filament. If the filament were cold, even a potential of 50,000 volts would not produce the slightest plate current.

The plate current at the point C is termed the *saturation current* of the valve. This current remains practically constant, and therefore the curve proceeds almost on the level to the right of C. As a matter of fact, it rises *very* slightly on account of the few additional electrons which only join the plate current when the plate is at a very high potential. Consequently, the term "saturation point" is not very definite.

The saturation current may, to all intents and purposes, be considered equal to the electron current emitted by the filament. If anything, it is slightly less, because it is *impossible* to draw up to the plate *every single* electron emitted. The question of space charge is no longer relevant. Up to a point, the space charge *is* a factor which tends to limit the plate current. Even as the plate voltage, and therefore its attractive power, is increased, the repulsion of the space charge remains an important factor because there is a large quantity of electrons between the filament and plate. As saturation point is approached, this quantity of electrons increases very slowly, while the attractive force of the plate, which counteracts the space charge, increases as usual. Experiment, moreover, shows that even if we place a strong positive charge close to the filament * no increase of plate current is observed, indicating that the saturation current of the valve is a fair estimate of the electron emission from the filament. (If, however, we had placed the positive charge close to the filament when the plate current was at a value near A, there would have been a decided increase in plate current, indicating the effectiveness of the repulsion exercised by the space charge.)

Representative Point.—When we are using 140 volts on the plate of our valve we are working it under special conditions. For example, a further increase of plate voltage will produce no increase of plate current. Instead of enumerating all the various conditions, we can convey everything by simply

* This may be done by means of a grid, as will be seen later.

referring to the curve of Fig. 25 and saying that the valve is being worked at the point C. The point C may be termed the *representative point* since it represents various special conditions. We immediately picture the characteristic curve and the existing conditions, which could not be done were we simply told that the plate potential was 140 volts and the filament current 0·6 ampere. Similarly A and B are representative points. Instead of saying that we have reduced the plate voltage from 140 volts to 20 volts, it is much more expressive to state that the representative point has moved from the position C to the position A.

Effect of Increased Filament Current on Voltage-Current Curve.—In Fig. 25 our filament current was 0·6 ampere, and we saw that saturation point was reached when the plate potential was about 140 volts. If now we increase the electron emission by increasing the potential difference across the filament from 3·5 volts to 4 volts the number of available electrons has been increased to $70 \times (1{\cdot}59 \times 10^{15})$ per second.* As we increase our plate voltage from zero, we obtain a second curve, ABED (Fig. 27), which, it will be noticed, follows the curve ABC as far as B. After the point B the curve goes straight on and, later on, bends over to the right to its saturation point D.

The plate, when at a certain voltage, is only capable of attracting a certain number of electrons. We saw that in the case of the ABC curve a potential on the plate of +40 volts was capable of drawing up $10 \times (1{\cdot}59 \times 10^{15})$ electrons per second. Actually $27 \times (1{\cdot}59 \times 10^{15})$ were emitted from the filament, so that $17 \times (1{\cdot}59 \times 10^{15})$ were wasted and simply returned to their source. In the case of our ABD curve 40 volts is still only capable of attracting $10 \times (1{\cdot}59 \times 10^{15})$ electrons per second. The number emitted, however, has increased to $70 \times (1{\cdot}59 \times 10^{15})$, so that the wastage is greater and $60 \times (1{\cdot}59 \times 10^{15})$ return to the filament. The same happens all along the ABC curve up to the point B, where conditions begin to change. At the point B of the ABC curve there are only $7 \times (1{\cdot}59 \times 10^{15})$ electrons to be drawn up before saturation point is reached. Considerable extra potential is required to draw up these reluctant electrons; the curve consequently bends over to the right. In the case

* This figure represents the saturation current of the 4-volt curve of Fig. 27.

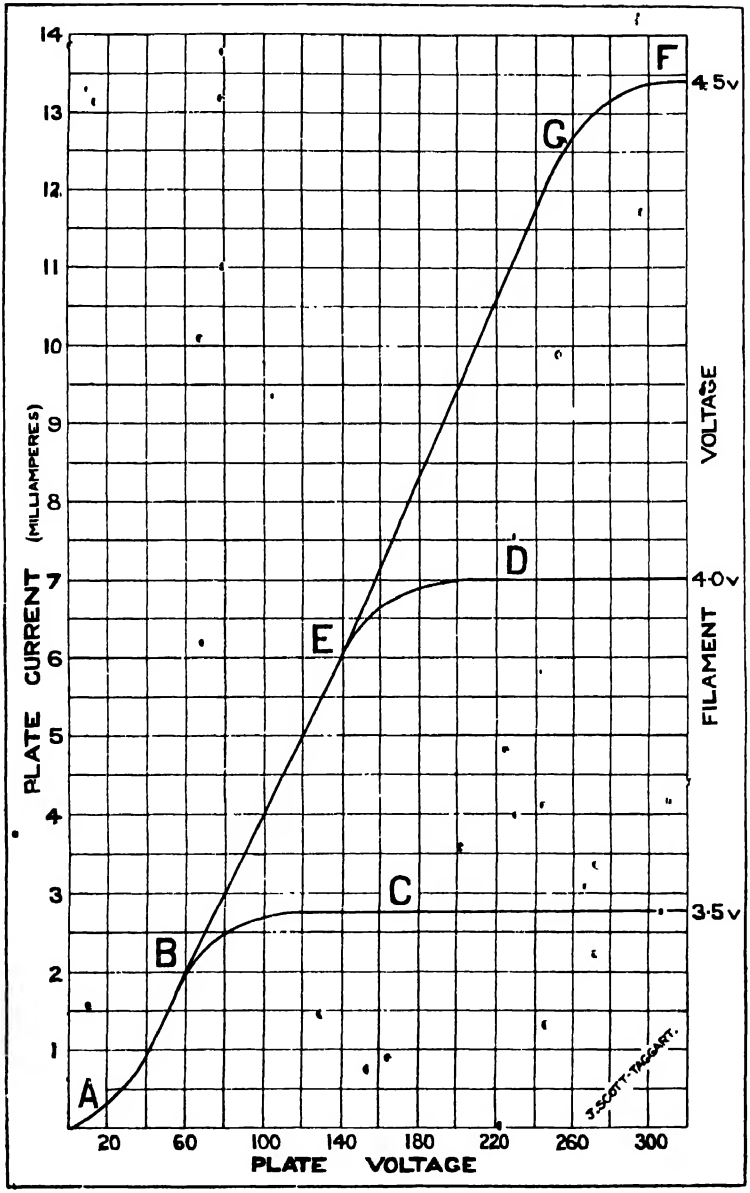


FIG. 27.—Effect of plate voltage on plate current at different filament voltages.

of the ABD curve, at the point B there are still $50 \times (1{\cdot}59 \times 10^{15})$ electrons which require to be drawn up. Moreover, this number includes many "willing" electrons which only need the normal increase of voltage to draw them to the plate. The curve, therefore, above B is a continuation of the part AB and does not begin to bend over to the right until the point E is reached. At E, however, the number of electrons not drawn to the plate is $10 \times (1{\cdot}59 \times 10^{15})$. These electrons are much more reluctant and only agree to go to the plate when its potential is considerably increased. The curve, therefore, bends over to the right and saturation point is reached at D, when the plate is drawing up all the $70 \times (1{\cdot}59 \times 10^{15})$ electrons emitted from the filament.

Exactly the same reasoning applies to the curve ABEGF, obtained when the potential across the filament is raised to 4·5 volts. The author proposes to call the points B, E and G *initial saturation points*, and the points C, D and F *final saturation points*.

We may summarise the above facts in the following statements:

(1) When the valve is worked *below* the *final* point of saturation an increase of plate voltage will cause an increase in the plate current.

(2) If the valve is worked *below* the *initial* point of saturation and the electron emission be increased, no increase of plate current will result.*

(3) If the representative point be *above* the *initial* point of saturation an increase of electron emission will cause an increase in the plate current.

(4) For each value of filament temperature (or, in other words, filament current) there is a certain value of plate voltage required to produce saturation. Three is a distinct series of saturation points for a corresponding series of filament temperatures.

Temperature Limitation.—We see from the above that the current through the valve is limited by the temperature of the filament. Saturation point is reached because of the *temperature limitation of the filament.*

The Filament-current—Plate-current Curve.—Although the curves of Fig. 27 are the most important, it will be as well here to discuss another characteristic curve of the simple two-electrode

* Frequently, in practice, a very slight increase results.

valve. Fig. 28 shows a curve ABC which illustrates the effect on the plate current when the filament current is gradually increased; this time it is the *plate voltage* which is kept constant. We will first keep this plate voltage constant at 100 volts when the conditions are represented by the curve ABC.

At zero current, the filament is cold and therefore no plate current exists. As we increase the filament current we raise the temperature of the filament until at 0·1 ampere the latter becomes incandescent and electrons begin to be emitted. The number is at first small. For example, at 0·2 ampere the number is only $1 \times (1 \cdot 59 \times 10^{15})$ per second. Practically all the electrons emitted pass to the plate, since the latter is at a relatively high potential, namely +100 volts. As we increase the filament current, at each value the +100 volts potential on the plate attracts all the electrons emitted at that value, and so the curve is more or less uniform. It will therefore be seen that the plate current is equivalent to the actual electron emission. This emission obeys Richardson's Law previously stated, and therefore the lower part of our curve would coincide with one drawn to Richardson's equation. As we increase the electron emission from our filament the space between filament and plate becomes filled with electrons on their way to the plate. This cloud of electrons possess the properties of a negative charge in space, and as it becomes denser it seriously limits the plate current. The repulsion of the space charge is also due in the later stages to the cloud of unwanted electrons surrounding the filament.

A point is finally reached when the space charge opposes any further flow of electrons to the plate, and the latter is incapable of attracting more than a limited number, which in our case is $55 \times (1 \cdot 59 \times 10^{15})$ per second. The saturation effect commences when the filament current is 0·74 ampere, and the plate current ceases to change when the filament current is above 0·97 ampere.

At the initial point of saturation B, the plate is *just* sufficiently positive to draw all the electrons emitted by the filament when its current is 0·74 ampere. If the voltage of the plate were increased, say, to 150 volts (curve ABFG), no further plate current would result. If it were reduced, say, to 50 volts (curve ADE), it would be insufficient to draw all the electrons emitted at the particular filament amperage we are considering (0·74 ampere).

To the right of the final saturation point C the curve remains level. The electron emission increases but produces

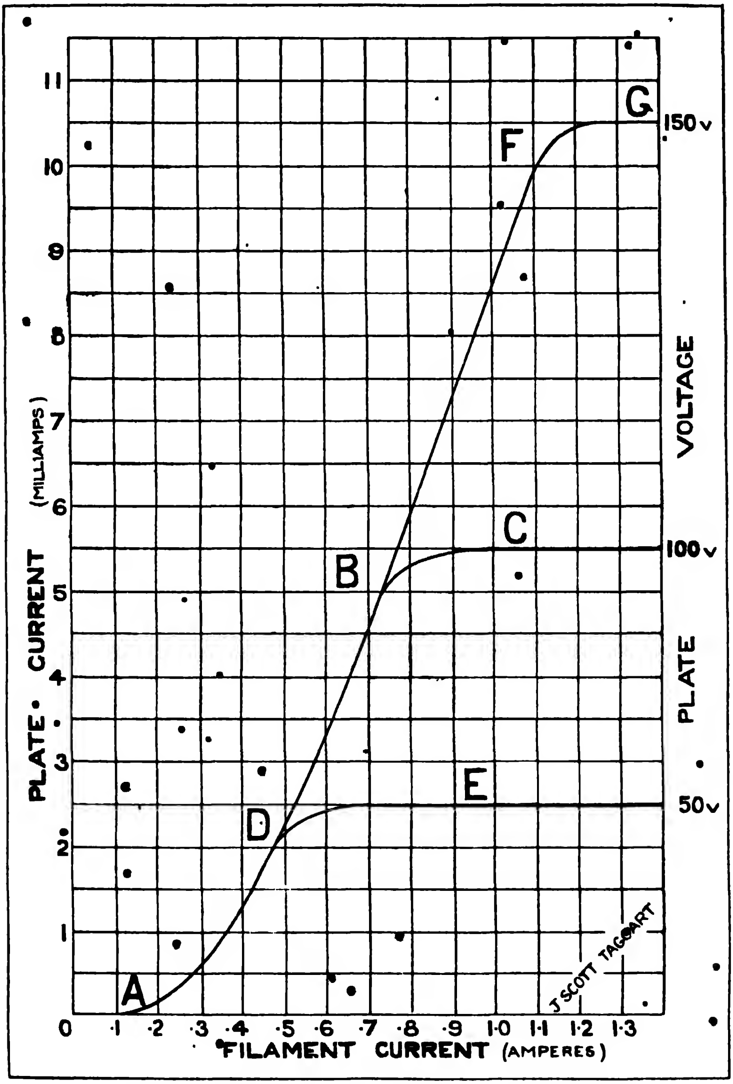


FIG. 28.—Effect on the plate current of increasing the filament current.

no increase in the plate current. The plate is sated, as it were, and in order to produce greater plate currents we will have to

increase our plate voltage. We have done this in the ABFG curve of Fig. 28. The saturation current is higher than before, but the curve bends over in a similar way to the ABC curve. If the plate voltage be made very high and the filament current increased, the filament will burn out through the excessive filament current long before the curve shows signs of bending over.

It is interesting to compare the Fig. 28 curves with those of Fig. 27. At the point A in Fig. 27 the plate can only draw up $3 \times (1{\cdot}59 \times 10^{15})$ electrons in spite of the fact that very many are actually being emitted from the filament. The conditions at A, or any other point below B, are therefore similar to those existing at representative points to the right of the final saturation bends of Fig. 28. At C (Fig. 27) the plate is able to draw up all the electrons emitted from the filament. The conditions at C are therefore comparable to those existing at B on the ABC curve of Fig. 28. In actual practice the higher voltage curves of Fig. 28 usually branch out a little to the left.

It is interesting to note that it was C. D. Child who in 1911 pointed out that the limitation of plate current at saturation point was due to the space charge effect of the electrons in the space between filament and plate. (This *space-charge limitation* is quite distinct from the *temperature limitation* produced when the plate voltage is sufficiently high to draw up all the electrons emitted.)

Assuming that in the space only ions of one sign are present, Child deduced the equation—*

$$I = \frac{1}{9\pi}\sqrt{\frac{2e}{m}} \cdot \frac{V^{\frac{3}{2}}}{x^2},$$

where

I=thermionic current per square centimetre of cathode surface,
V = voltage between anode and cathode,
x = distance between them,
e = charge of electron,
m = mass of electron.

This equation was deduced on the assumption that both cathode and anode are equipotential surfaces of infinite extent.

Further Remarks on Electron Emission.—Langmuir has found that the thermionic current obtained from an in-

* C. D. Child, *Phys. Rev.*, **32**, 498 (1911). The space charge has been fully studied by J. Lilienfeld, *Ann. d. Phys.*, **32**, 673 (1910); I. Langmuir, *Phys. Rev.*, (2), **2**, 450 (1913), who also independently derived the space charge equation; see also Schottky, *Jahrb. d. Rad. u. Electronik*, **12**, 147 (1915).

candescent filament measured in milliamps. per square centimetre is represented by

$$I = 29{\cdot}6 \times 10^9 \sqrt{T}\,\epsilon^{-52{,}500/T}$$

where T is the absolute temperature of the filament, the absolute temperature being equal to the Centigrade temperature plus 273°. The symbol ϵ is the base of Napierian logarithms and is 2·718.

Saul Dushman * gives the following table showing the thermionic current per square centimetre surface area emitted from a tungsten filament at different temperatures.

T. (absolute).	i = milliamps. per sq. cm
2000	4·2
2100	15·1
2200	48·3
2300	137·7
2400	364·8
2500	891·0
2600	2044·0

The same author also gives the following valuable table showing diameter of filament in mils (1 mil=0·001 inch), the temperature of the filament at which it may safely work for 2000 hours, the thermionic current per centimetre length, and also the power consumed in heating the filament (filament volts multiplied by filament amperes). It is to be noted that impurities in the tungsten cause large variations from these figures. The presence of thoria, for instance, greatly increases the emission.

Diameter of filament in mils.	Safe temperature (absolute).	Thermionic current in milliamps. per centimetre length.	Watts expended in heating one centimetre length of filament.
	Deg. K (Kelvin).		
	2475	30	3·1
	2500	50	4·6
10	2550	100	7·2
15	[illegible]	200	11·3

Simple Valve Action explained by Means of Curve.—We have seen that if one side of the closed circuit inductance be connected to the plate of a valve and the other side to the negative of the filament, the arrangement will act as a detector (Fig. 21). We can easily understand the reason for this when

* Saul Dushman, *General Electric Review*, March, 1915, xviii. p. 156. Also abstract *Electrician*, May 28, 1915. A still deeper study has been made of electron emission by G. Stead, *Journal of Institution of Electrical Engineers*, 58, 287, 107.

we look at Fig. 29, which shows an example of the curve connecting plate voltage and plate current. The curve

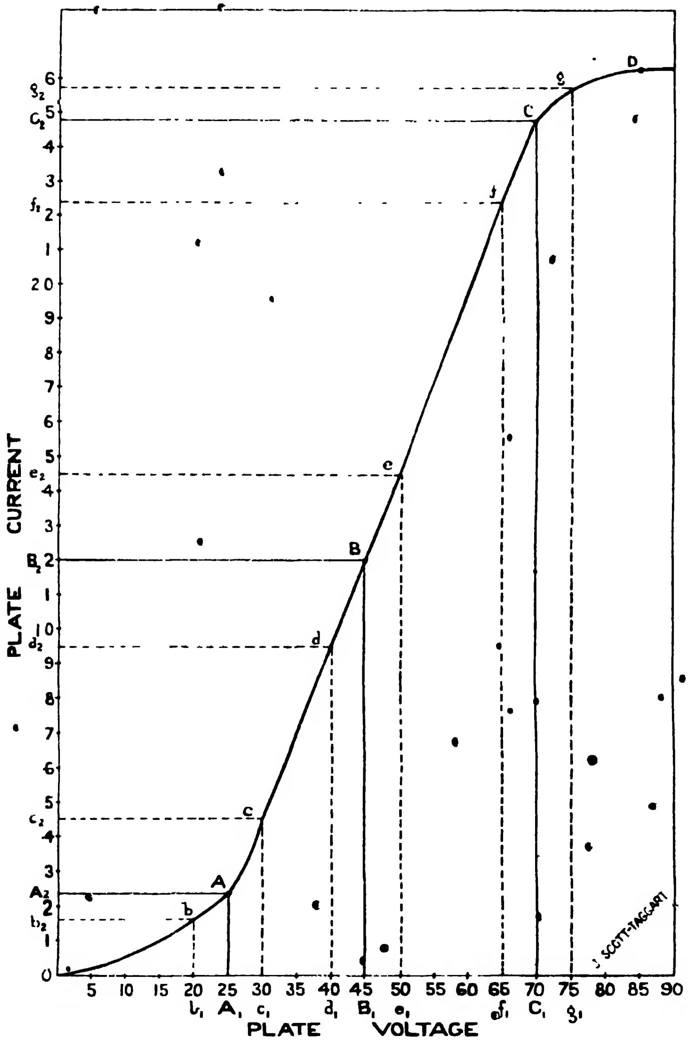


FIG. 29. Effect of an alternation at different points of the curve. Fil. current – 0·6 amp.

commences at the *origin* O. When the plate is at a negative potential there is no electron flow in either direction. When

positive half-cycles influence the plate the latter receives a positive charge, and the representative point moves from O along the curve to a point determined by the voltage to which the plate is raised. The plate current starts at zero and increases to a value determined by the ultimate potential of the plate. If now a negative half-cycle influences the plate no current will flow to the plate. Consequently alternating or oscillating current will be rectified by using the valve at the point O.

Drop of Potential due to Establishment of Electron Current.—The ultimate potential, be it noted, is not equal to the E.M.F. of the positive half-cycle of oscillating current. The capacity of the plate is very small and absorbs practically no energy; on the other hand, the establishment of a plate current automatically causes a drop in plate potential depending on the strength of the resultant current. This effect is comparable to that produced when an external circuit is connected across a battery of, say, 10 volts. The external voltage of the battery drops immediately to a lower value. The less the external resistance the greater the drop of voltage. In the curve of Fig. 29, the plate voltages are those existing while the plate current is flowing. This point, however, is a minor one at this stage.

Use of Lower Bend of Curve for Rectification.—Although the point O of the curve gives useful results, still better ones are obtained when either the point A or the point C is used.

The theoretical action of the valve at the point A is as follows:—Supposing our filament current is 0·6 ampere, and our normal plate voltage A_1 is 25 volts; then these conditions are represented by the point A of the curve OACD. The normal plate current is A_2 (0·24 milliamp.).

An oscillating current is supposed to change the voltage of the plate first by +5 volts (or practically that amount) and then by −5 volts. The positive half-cycle increase the plate potential from its normal value A_1, 25 volts, to c_1, 30 volts. The representative point therefore moves to the position c, and the plate current increases to c_2. This is a change from 0·24 milliampere, to 0·45 milliampere, and is an increase of 0·21 milliampere.

When, however, the negative half-cycle comes along, it causes the plate voltage to drop 5 volts to the position b_1, corresponding to a plate potential of 20 volts. The repre-

sentative point therefore moves from A along the curve to b, and the plate current falls from A_2 to b_2. This means a change from the normal value 0·24 milliampere to 0·16 milliampere, a drop of 0·08 milliampere.

Now the point to notice is that the increase of current due to +5 volts is greater than the decrease due to −5 volts. Although $A_1c_1 = A_1b_1$, yet A_2c_2 is greater than A_2b_2. The effect, therefore, of an alternating or oscillating current of 5 volt amplitude impressed on the plate when the latter is at +25 volts, is to cause an *average increase* in the plate current. We have, therefore, rectified our oscillating currents to a certain extent, since negative half-oscillations produce only a very small variation of the normal plate current. In other words, we have taken advantage of the *non-linear characteristics* of the plate-current curve.

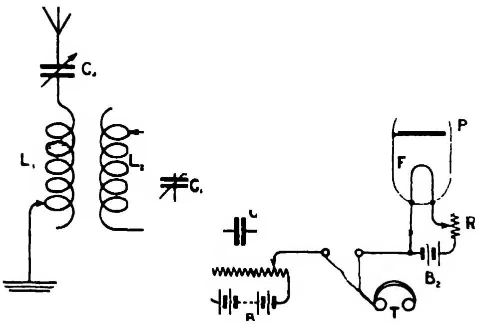


FIG. 30.—Fleming valve circuit for using bends of the characteristic curve.

Fig. 30 shows a Fleming valve circuit which utilises the point A for rectification. The potential of the plate is variable by means of the potentiometer P. Any of the previously described methods of applying potential may be used instead, if desired. In the plate circuit is also included a pair of telephones, T, of high resistance. The small condenser C_2 serves to allow the passage of H.F. potentials and to accumulate the rectified charge. The potentiometer P is varied until the loudest signals are heard in the telephones.

Fig. 31 shows the process when the valve is adjusted by means of the potentiometer to the point A of its curve (Fig. 29). In Fig. 31 the top line shows the incoming wave-trains. The second line shows the effect of the oscillations on the plate current. The line AB represents the normal plate current. The dotted line shows the average increase of plate current due to incoming signals. The *average* effect of each complete oscillation is to increase the normal current passing through

the 'phones. Since the oscillations have a very high frequency (500,000 per second in the case of 600 metre waves), the diaphragm of the telephone cannot respond to each individual increase of plate current. Instead, it responds to the average effect of the wave-train, and a click is produced for each group of oscillations. The third line of Fig. 31 represents the unidirectional *audio-frequency* pulses passing through T. It will be easily understood that, when signals are not being

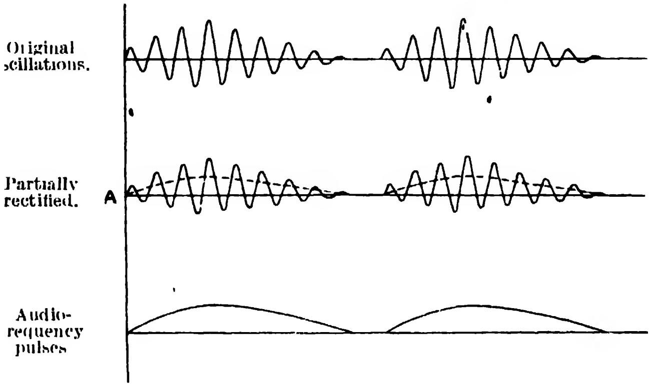


FIG. 31.—Graphical representation of rectification obtained at lower bend of plate current curve.

received, the steady current through the 'phones will produce no sound. It is the *variation* of the normal current through the telephones that produces the sound.

Effect of using Midway Point along Curve.—Any adjustment of plate voltage which brings the representative point in the neighbourhood of the lower bend, will result in signals being received. If, however, we adjust the plate voltage so that the representative point is situated on the steep, straight portion of the curve, no signals whatever will be received. Such a point is B in Fig. 29. This point is obtained by placing 45 volts on the plate. The normal plate current B_2 is 1·2 milliamperes. When signals are being received, we will suppose that a complete oscillation varies the plate voltage first from B_1 to e_1, and back, and then from B_1 to d_1, and back. We are presuming that $B_1d_1 = B_1e_1$.* While the plate

* To be strictly accurate, this is not so in the case of damped wave trains. The two halves of an oscillation are not quite equal. Also the actual values of B_1e_1 and $B\ d_1$ start small, increase to a maximum, and then decrease again for each damped wave train.

voltage is increasing, the representative point moves up the curve to the final position *e*. The plate current increases from its normal value B_2 to e_2, which represents an increase of 0·25 milliampere. The representative point then returns along the curve and reaches B at the end of the positive half-oscillation. As the negative half decreases the value of the plate voltage, the point moves down the curve and takes up the position *d*. The plate current falls correspondingly from its normal value B_2 to d_2, a decrease of 0·25 milliampere. It will therefore be seen that *equal* increases and decreases of plate voltage produce *equal* increases and decreases of plate current. There will therefore be *no rectification*, and no signals will be obtained at B or similar points.

Rectification at the Final Saturation Point.—For the same reasons that we obtained rectification at the commencement O of our curve, we would expect to receive signals at the end D. This point is what the author chooses to call the *final saturation point*, where the current ceases to increase, except minutely. It is the right-hand end of the bend (D). If our plate voltage be adjusted to 85 volts so that the representative point is at D, positive half-cycles, although increasing the voltage of the plate, cannot cause any further increase of plate current since the valve is saturated. Negative half-cycles, on the other hand, will reduce the plate voltage and the plate current will decrease slightly. The effect, therefore, of a series of alternations or oscillations is to cause a *fall* in the normal current flowing through the plate circuit, and therefore through the 'phones.

Rectification at the Initial Saturation Point.—If we adjust the plate voltage to 70 volts, our representative point C will be at the *initial saturation point*, where the plate current *just* begins to increase more slowly, and the curve leans over to the right. At this point we get rectification for the same reason that we obtained it at the lower bend A. There is, however, this difference: At the point C, positive half-cycles cause only small increases of plate current, while negative half-cycles cause the representative point to descend the steep slope to the left of C. The decrease of plate current for negative half-cycles is therefore greater than the increase for positive half-cycles. The effect, then, of incoming oscillations is to cause an average *drop* in the value of the plate current, whereas, when the lower bend A was used, oscillations produced an average *increase*.

Imperfect Rectification with Amplification as against Perfect Rectification.—We have seen that when we adjust our valve to the points O or D (especially O *) of its curve we get practically pure rectification. In the case of the beginning O of the curve, a current will only flow when positive half-cycles affect the plate. In the case of D, a variation of the normal plate current is only effected by negative half-cycles. We might, therefore, imagine that, since the rectification is perfect, these are the best *operating points*. In practice, however, we generally find the best points for receiving are on the lower and upper bends of the curve. The reason is simple. Although the rectification at O may be theoretically perfect, yet the *actual currents obtained* are small. As will be seen from Fig. 29, the curve to the right of O slopes very gradually. Similarly, the curve to the left of D also slopes gradually, and represents only a very slight drop in plate current for decreases of plate voltage. If the curve rose steeply from O, or if D were a sharp bend where the plate current suddenly decreased, these points would be almost ideal.

At A, although there is a variation of the mean plate current for *negative* as well as positive half-cycles, yet the resultant *average* increase of current is a considerable one, and is capable of giving louder signals in the telephones than the weak currents obtained when the point O is used. The two-electrode valve may be considered to be acting as a kind of *amplifier*. Incoming oscillations vary the current A_2 flowing in a local circuit. (The modified Fleming valve circuit of Fig. 34, which is capable of receiving signals, shows more clearly the two circuits, local and oscillatory.)

From this we see that although we do obtain pure rectification at the points A and C, yet this is more than compensated by what might be called the *amplifying* or relaying † action at these points. The effect is rather similar to that obtained with a carborundum detector.

Generalised Conditions for Rectification.—In the left-hand column of Fig. 32 is a series of *concave* curves such as are met with on the various characteristic curves of valves as usually drawn. The line XY represents the ordinate, or vertical line, passing through, say, the normal plate potential, assuming we

* Because the saturation bend is generally gradual and the position of D is vague.

† The word "relay" really implies that the local effect is definite and does not depend on the strength of the influencing impulses.

are using a graph of the Fig. 25 type. The line PQ represents a decrease of 1 volt in the plate potential due to negative half-oscillations. The line RS represents an increase of 1 volt due to positive half-cycles. The distance *bc* represents the increase of current and *ba* the decrease.

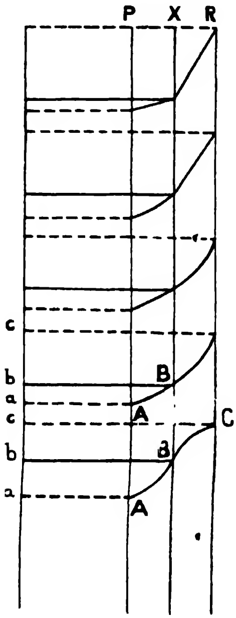


FIG. 32.—Examples of rectification obtained at operating points on different curves except in the case of the bottom left-hand curve.

The curves are all concave but differ from each other. The point A, however, is always lower than B. It will be seen that in all cases the increase *bc* is greater than the decrease *ba*. In the top curve there is a very critical bend at B, but it must be noticed from the other curves that a *critical* bend is not essential to rectification. The fact that the curve is concave is sufficient.

In the right-hand column of Fig. 32 is a series of convex curves. This time it will be seen that the *decreases* of current are always greater than the increases. Again we see that smooth curves can produce rectification.

In addition to the curves of Fig. 32, there are special ones which, however, are not usually met with in valve work. For example, if A were higher than B, it would mean that both positive and negative half-cycles produced an increase of current. Similarly, if both A and C were below B, both half-cycles would cause a decrease of current.* Other cases may be worked out by the reader himself. If the curve is partly convex and partly concave, as in the case of the bottom left-

* Such a point is obtained in three-electrode valves to the right of the saturation point, if the grid potentials are high enough.

hand curve of Fig. 32, there is no rectification. The result is almost the same as if the curve were a straight line.

We can summarise the above remarks in the following statements, which apply to the type of curves given in Fig. 25:—

(1) If the portion of the curve used (*i.e.* the part along which the representative point travels) is straight, there will be no appreciable rectification of currents of an alternating nature.

(2) If the portion of the curve is concave, there will be rectification resulting in an average *increase* of normal current.

(3) If the portion of the curve is convex, there will be rectification resulting in an average *decrease* of normal current.

Critical Points for Different Strengths of Incoming Signals.—From the above remarks, we can easily understand why signals may be heard at almost any adjustment of the valve. Unless this adjustment is in the neighbourhood of the point B of Fig. 29, the ordinate through the normal plate voltage is almost bound to cut a curve of some sort.

An interesting fact is that the critical position of the representative point suitable for the reception of strong signals is not generally the same as that for weak signals. In other words, the best adjustment of the valve depends to a certain extent on the strength of incoming oscillations.

Methods of adjusting Valve to Critical Point for Reception.—The obvious way to make the representative point coincide with the critical point on the curve which gives the best results, is to vary the voltage of the plate.

If, however, we are using the saturation bend as our rectifying point, we can arrive at this adjustment by keeping our plate voltage constant and gradually varying the filament current. The effect of increasing the filament current is to increase the height of the curve and also to move the saturation point to the right (Fig. 27). We can therefore adjust the saturation point to such a position that it is cut by the vertical ordinate passing through our normal plate voltage. Suppose this latter to be 140 volts and we desire to use the initial point of saturation for the purposes of rectifying. If we make the filament voltage 3·5 volts, the representative point is too much to the right (curve ABC, Fig. 27). If we increase the filament current gradually, the representative

point will move to positions relatively lower down the curve, until at 4 volts the valve will be adjusted to the initial point of saturation E (curve ABED). A further increase of filament current will cause us to use the valve at a point lower than we desire (curve ABEGF).

This example of moving the representative point to a desired position by means of the filament current will serve as an introduction to what is very frequently done in all applications of the *three-electrode* valve, which we are about to consider.

Practical Fleming Valve Circuit.—A practical circuit for use with the Fleming valve is that shown in Fig. 33. It will be seen that the filament current is variable by means of the rheostat R, and the plate receives a variable potential by means of a potentiometer arrangement connected across the lighting accumulator. The following are points to note and remember, because they apply equally well to circuits using modern three-electrode valves.

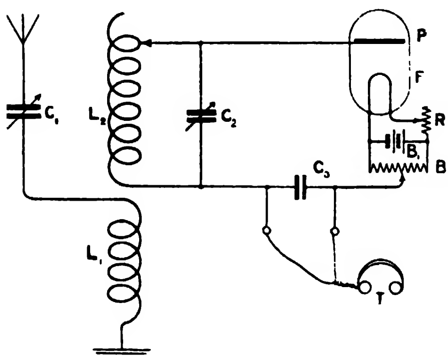


FIG. 33.—A Fleming valve [illegible]iving circuit

(1) The tuning of the closed circuit should be accomplished chiefly by the inductance L_2. The value of the variable condenser C_2 for the very best results should not exceed about 0·000002 mfd. It is only sufficiently large to give fine tuning. If larger values be used, the efficiency of the arrangement will be impaired. Larger values, however, are much more convenient for tuning purposes. An endeavour should be made, when tuning, to keep the value of the condenser capacity as low as possible.

(2) The plate of the valve is connected to the *high-potential end* of L_2. This is the end furthest away from the earth side of L_1. If the high-potential end of L_2 be touched with the finger, signals will be reduced. If the *low-potential* end be touched, no such effect

is noticed. Reversing the connections to the valve will, of course, indicate which way is the better.

(3) The telephones should be included in the circuit at the low-potential part next to the filament and not between the plate and L_2. The lighting accumulator may practically always be considered as being earthed; the operator may also be so considered. If he is wearing the 'phones, and the latter be included in the plate circuit near the plate, a reduction in the potential induced at the top end of L_2 will be the result. Moreover, the inductance L_2 is liable to be slightly shorted through faulty insulation of the 'phones.

(4) Since the plate circuit is of high resistance (above 10,000 ohms), the 'phones T should also be of high-resistance, say 4000 ohms. The detector is essentially a potential-operated one.

Modified Fleming Valve Circuit.—A modified Fleming valve circuit is shown in Fig. The condenser C_3 prevents the high-tension battery H shorting through inductance L_2. The circuit is only interesting at this modern period because it shows clearly the two circuits, oscillatory and local.

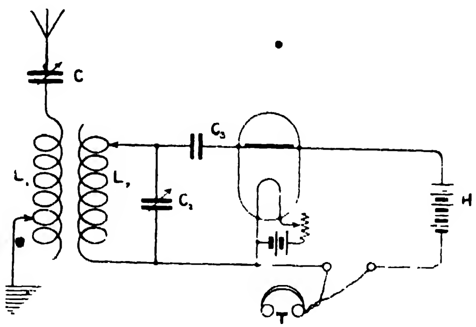


FIG. 34. Modified Fleming valve circuit.

Use of Telephone Transformer. -- A telephone transformer may be included in the plate circuit of a Fleming valve. It has two windings, usually a high-resistance one of about 4000 ohms and a low-resistance one of about 60 ohms. The high-resistance winding is included in the plate circuit of the valve and 60-ohm telephone receivers are connected to the low-resistance winding. When the plate current is steady, there is no current in the low-resistance winding. If the plate current varies at all, currents will be set up in the low-resistance winding by induction and will affect the telephones.

Below are some of the disadvantages of connecting the 'phones directly in the plate circuit. They are overcome by the use of a telephone transformer, which is highly desirable in nearly all valve circuits.

(1) If 'phones are connected permanently in the plate circuit of a valve, they are liable to be connected in such a way that the steady current demagnetises them and lessens their sensitiveness.

(2 The high voltage of the plate circuit is liable to cause a breakdown of the insulation of the 'phones if they are included directly in the circuit.

(3) Crackly noises are almost invariably, heard in the 'phones when the latter are directly in the plate circuit. They are due to leakage and bad insulation of the windings, which are apt to get moist when the 'phones are continually worn.

(4) The operator is liable to get shocks unless a telephone transformer is used.

(5) In many valve circuits which have the 'phones directly in the plate circuit. singing noises are heard if the 'phones be touched or their position on the head altered.

Rectification at Saturation Point of Temperature Curve.—In Fig. 28 we saw that if we kept the plate voltage constant and increased the filament current a point C was reached when a further increase of filament current produced no increase in the plate current. This phenomenon may be used to rectify alternating currents by employing the circuit shown in Fig. 35. The filament current is varied by means of R, and passes through the secondary of a transformer T. To the primary of this transformer is connected the alternating current supply.

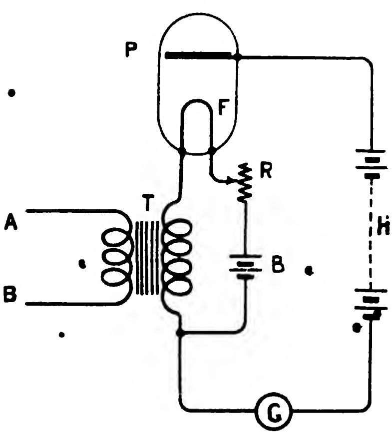


FIG. 35.—Circuit for rectification at saturation point of temperature curve.

The filament current is adjusted so that the point C

represents the conditions. The alternating current which is made to flow in the filament circuit alternately aids and opposes the lighting accumulator. The filament current, therefore, increases and decreases in turn. When it increases, there is no change in the plate current measured by G. When it decreases, the plate current falls in value. The effect, therefore, is equivalent to the rectification of the original alternations. The point B (Fig. 28) might also be used. It is to be noted that the alternations will have to be of low frequency in order that the temperature of the filament shall have time to change.

Brown's Ionic Relay.– In British Patent 104566, S. G. Brown describes a telephone relay somewhat similar to Fig. 35. He uses the *straight* portion of the valve curve and obtains amplification of any current variations passing through the primary of T. In place of G, he uses a telephone to detect the amplified current. Such an arrangement would be suitable for amplifying unidirectional pulses obtained by the rectification of wireless oscillations. It would also be suitable for amplifying any current variations of low frequency.

The Apparent Resistance of a Valve.—Since the current through a valve does not vary according to Ohm's Law, its resistance, or *apparent resistance*, varies. For example, in the case of Fig. 29, 20 volts across plate and filament give rise to a plate current of 0·00016 ampere. The apparent resistance of the valve (neglecting the relatively small resistance of the plate battery) is therefore 125,000 ohms. If now we place 30 volts across the valve, the plate current obtained is 0·00045 ampere. The apparent resistance of the valve is now 66,700 ohms, a value much less than that previously obtained.

Fig. 36 is a curve corresponding to Fig. 29, but showing the variation of the apparent resistance of the valve obtained from the formula :

$$R = \frac{V}{I}$$

Similar curves could be drawn for each value of filament current. It is to be noted that the resistance of the valve is least at the initial saturation point.

Further Analysis of the Rectification Process.—In Fig. 37 we see a typical characteristic curve of a valve being used as a detector. The curve shows the plate current plotted on the

y axis as a function of the plate voltage, which is plotted on the x axis. Later, we will be using somewhat similar curves representing conditions existing in a three-electrode vacuum

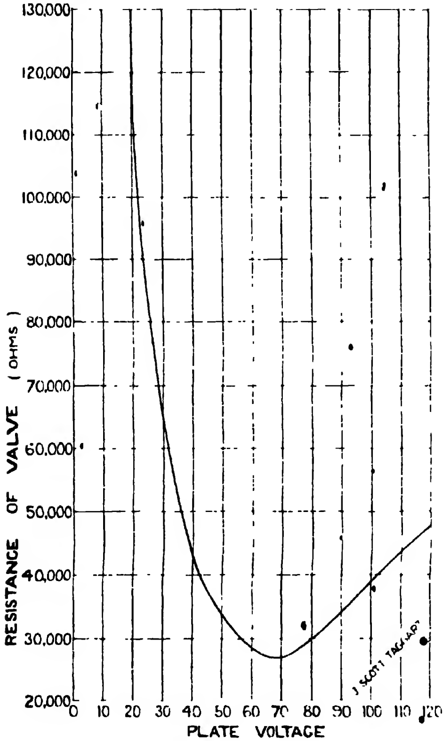


FIG. 36.—Showing variation of the apparent resistance of a valve.

tube. The following remarks will apply to those curves as well as the two-electrode valve curves under consideration.

The normal voltage of the plate * is E_0. The normal plate current is represented by the ordinate E_0I_0, I_0 being the representative point on the curve at which we are working the valve. We will now suppose that incoming signals vary

* Or grid, as it will be when discussing the three-electrode valve.

the plate potential from E_0 to E_1 in the case of positive half-cycles, and from E_0 to E_2 for negative half-cycles. Let us also suppose that $E_0E_1 = E_0E_2$. Since the curve is concave, the increase of plate current due to the movement of the representative point from I_0 to I_1 will exceed the drop in plate current due to the point sliding down to I_2. The increase of plate current is represented by I_1B and the decrease by I_0C. The response in the telephones (connected in the plate circuit) is proportional to the mean value of the change in plate current, namely, $BI_1 - BX$ the line BX being equal to I_0C, the decrease in plate current. If now we draw a *secant* I_1I_2 joining the extreme positions of the representative point, and if we produce E_0I_0 to cut this line at S, we may show that SI_0 represents the rectified current through the telephone receivers or their equivalent. The proof of this is as follows:

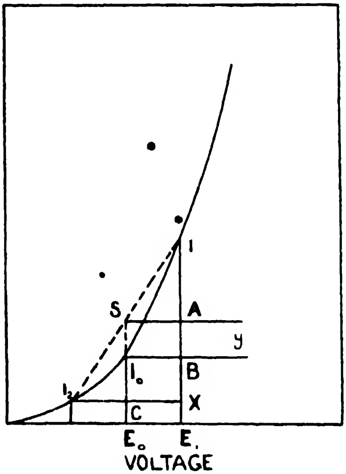


FIG. 37.—To demonstrate the process of rectification.

$$SI_0 = AB = AX - BX$$
$$2SI_0 = 2AX - 2BX$$

Now since $I_2C = CX$ and SC is parallel to I_1X,

$$I_1X (= I_1B + BX) = 2AX$$
$$\therefore \quad 2SI_0 = (I_1B + BX) - 2BX$$
$$= I_1B - BX$$
$$SI_0 = \frac{I_1B - BX}{}$$

By noting the distance SI_0 we have then a quick method of determining the efficiency of the curve for detecting purposes.

It might at first be thought that the rectified current would be proportional to the amplitude of incoming waves. This, however, would only be the case if the curve of Fig. 37 were a linear one. Actually, if we double the amplitude of the incoming waves we will get *four times* the rectified current. The rectified current is proportional to the square of the input voltage.

Rectification of Weak Signals Inefficient.—From the above considerations we see that if, say, we decrease the amplitude of our incoming oscillations by one-third (by using a smaller aerial, for example) our signals will be only one-*ninth* of their former value. For very weak oscillations, then, the rectification becomes negligible and our device—the vacuum tube—becomes very inefficient. It is, therefore, of the greatest advantage to increase the amplitude of our original oscillations as much as possible, thereby obtaining reasonably large movements or excursions of the representative point. Fortunately, one can increase the amplitude locally by various applications of the three-electrode vacuum tube, which we will now proceed to consider. The point to notice here is that rectification on a curve is only efficient for appreciably strong received oscillations.

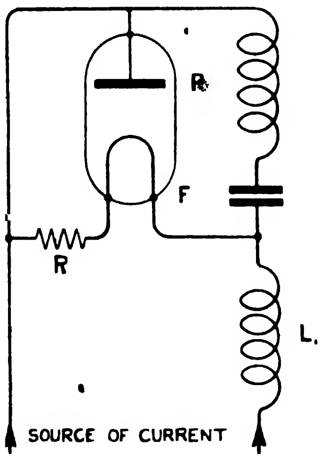


FIG. 38.—Two-electrode valve as a generator of continuous waves.

Two-electrode Valve as an Oscillator.*—In British Patent 72/08 (Jan. 1/08), S. Eisenstein shows a circuit in which a two-electrode vacuum tube acts as an oscillator, and is capable of generating continuous waves. The circuit is shown in Fig. 38. The filament is heated by a source of current through a resistance R and an inductance L_1. An inductance L_2 and a capacity C is connected across plate and filament of the valve.

Vapour Lamp Rectifier.—In British Patent 19034/05 (Sept. 20/05), the British Thomson-Houston (for the General Electric

* This effect is due to the valve possessing negative resistance characteristics under conditions comparable to those existing in an arc.

Company of U.S.A.) describe a valve receiver which consists of a vapour lamp in which an arc ionises the gas. Besides the arc electrodes there are two others which are connected across the receiving inductance, the middle point of which is connected to the arc, through the telephones.

CHAPTER II.

THE THREE-ELECTRODE VACUUM TUBE.

The Introduction of a Third Electrode.—So far, we have only considered the two-electrode valve of the Fleming type. This type of valve is hardly ever used except as a rectifier of alternating current. It has now given place to the three-electrode vacuum tube, which perhaps is a more correct name than a three-electrode "valve." W. H. Eccles has termed the device a "triode."

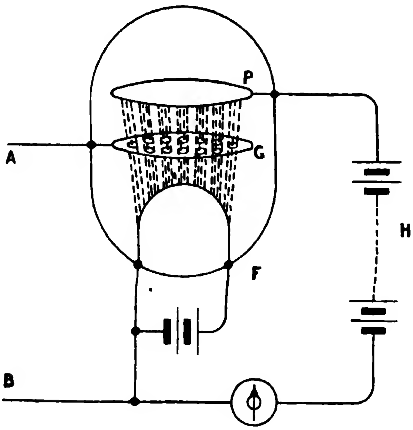


FIG. 39.—Showing passage of electrons to the plate through holes in the grid.

The essential feature of the three-electrode tube is the use of a *third electrode to control the flow of current from filament to plate.* This third electrode was introduced by Lee de Forest,* who claims that his "audion" or three-electrode tube was developed entirely independently of J. A. Fleming and was not a development of the latter's "valve." There has been considerable controversy over the question and also litigation.

Shortly afterwards, von Baeyer † used an auxiliary electrode, consisting of a wire gauze, to control the thermionic current between cathode and anode.

* De Forest, British Patent 1427/08 (Jan. 29/07), U.S. Patent 841387/07, and U.S. Patent 979532/08. *Vide* also Lee de Forest, *Electrician*, **58**, p. 216 (1906); and *Electrician*, **72**, p. 285 (1913).

† Von Baeyer, *Verh. d. Phys. Ges.*, **7**, 104 (1908).

The third electrode in a vacuum tube may take several forms. In its simplest form it consists of a metallic plate perforated by numerous holes, placed close to the filament and between it and the anode plate. Owing to its position, the electrons have to pass through the holes on their way to the plate. Fig. 39 shows a metallic filament F, an auxiliary electrode G (usually termed a "grid"), and a round metallic disc P. The dotted lines show the path taken by the electrons.

The grid may take any of the following forms, ich are examples :—

(1) A perforated metal plate placed between plate and filament inside the vacuum tube.

(2) A sheet of metal gauze similar to a sieve.

(3) A zig-zagged wire wound between two parallel glass supports.

(4) A spiral of wire or cylindrical gauze, when the plate is cylindrical.

(5) A metal coating G (Fig. 40), outside the glass of the tube.*

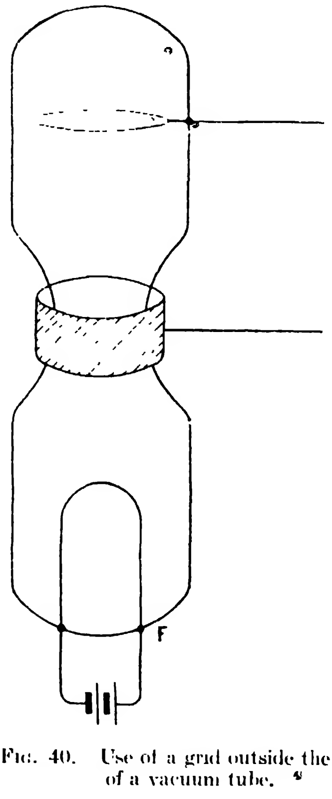


FIG. 40. Use of a grid outside the glass of a vacuum tube.

(6 In some types of valve introduced by the Western Electric Company (U.S.A.), the "grid" is not between the filament and plate. On the other hand, the filament is wound round—but insulated from—an electrode which acts as a grid (see Fig. 41). A layer of nickelous oxide is used as the insulator.

* Used in M.W.T. Co. and H. J. Round's British Patent 13247/14 (May 29/14). Also used in some of Weagant's circuits.

(7) Two grids are used by Q. Majorana, and a potential across them affects the plate current.*

(8) The present author has made and used a valve in which two flat plates are arranged on either side of a filament. One plate is used as an anode and the other as a grid.†

(9) J. Erskine-Murray ‡ has described a valve in which the grid is an electrode on the opposite side of the filament to the anode; a positive voltage on the "grid" will cause a *decrease* in the anode current.

The last two unusual types are described later.

The general tendency is to use a grid inside the tube and placed as close to the filament as possible.

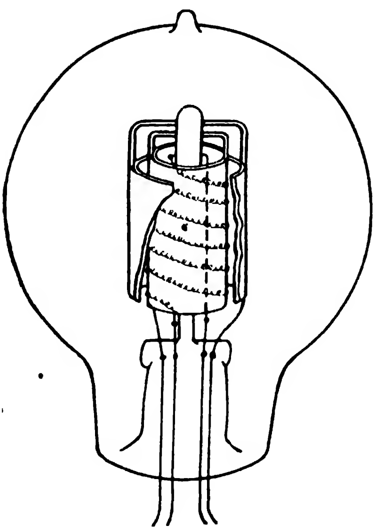


FIG. 41.—A Western Electric tube in which the filament is wound round but insulated from the grid.

The following particulars of a small valve capable of being used for all the purposes to which a valve is put, will, however, be of interest to the reader as giving him a conception of the relative sizes of the various parts.

Filament.—A straight tungsten wire 0·9 in. long and 0·0023 in. diameter.

Grid.—Spiral of molybdenum wire 0·18 in. diameter and 0·8 in. in length. Thirteen turns in the spiral.

Plate.—Nickel cylinder 0·6 in. long and 0·42 in diameter.

The valve is in general design similar to the one shown in Fig. 42, which is usually termed a French or "R" type.

The Audion, Round, and Lieben Vacuum Tubes.—The original "audion," as designed by Lee de Forest, consisted of three electrodes enclosed in an evacuated bulb containing gas

* British Patent 23024/12 (Oct. 9/12).

† J. Scott Taggart, *Electrical Review*, **86**, 261 (Feb. 27/20).

‡ British Patent 133413 (Oct. 4/18).

at low pressure. This gas played an important part in the operation of the device, and in all early patents one sees that bulbs containing ionisable gas are specified. We have, for example, the valve designed by H. J. Round of Marconi's

FIG. 42.—A typical three-electrode vacuum tube of the "French" type.

Wireless Telegraphy Company. This valve * is one of the best of its type. During operation, some of the gas molecules are disassociated into positive ions (sometimes termed *anions*), and electrons. The original electrons are emitted from a

* See British Patent 28413/13 (Dec. 9/13).

filament coated with oxides of the alkaline earths which produce a strong electron emission. The grid consists of a cylinder of copper gauze. and the plate is nickel and also cylindrical in form. At the top of the bulb is a small pocket opening into the tube and containing a pellet of asbestos or other suitable gas-occluding material. The pellet occludes some of the mercury vapour in the tube and the pressure of the vapour in the valve may thus be kept constant by heating the pocket when the pressure drops, as it does after a time.

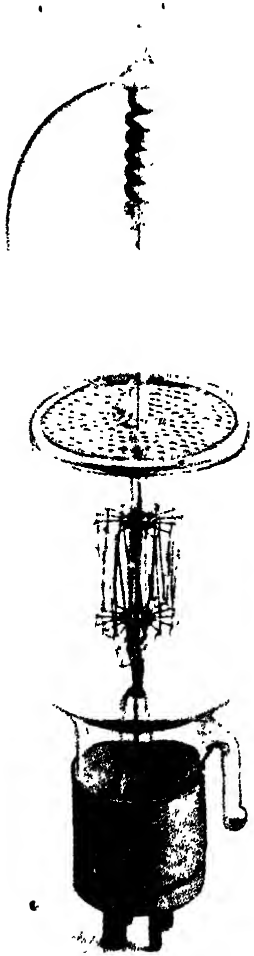


FIG. 43.—The Lieben Reisz vacuum tube.

Lieben and Reisz, of the German Telefunken Company, were amongst the first to use a grid between filament and plate.* Their valve is shown in Fig. 43. Their filament consisted of a platinum strip 1 metre (3 feet) in length, 1 mm. (0·04 in.) wide, and 0·02 mm. (0·0002 in.) thick. It was thinly coated with a mixture of calcium and barium oxides and brought to a red heat by a current of about 2 amperes from a 30-volt storage battery. The grid was a perforated aluminium disc, the size of the perforations being about 3·5 mm. (0·14 in.) diameter. The anode was not in the form of a plate, but consisted of a helix of aluminium

* British Patent 2111/11 (Jan. 19/11).

wire. All connections to the bulb are made through the bayonet sockets in the base. These sockets fit into plugs fixed on the base-board of the instrument using the vacuum tube. This system of making connections is very frequently used in modern valves. Fig. 44 shows a small compact valve, designed by the present author for the Edison Swan Electric Company, Ltd., for general use. Here the base is fitted with plugs in the form of split pins which fit into four sockets fixed on a valve holder. The plugs and sockets are arranged as shown in Fig. 45. This makes it impossible to put the valve into the holder incorrectly.*

FIG. 44.—A small three-electrode ES 1 type vacuum tube (J. Scott-Taggart).

The original Lieben-Reisz tube was, as in the case of all earlier valves, a "soft" vacuum tube.† The gas inside was mercury vapour at the ordinary pressure of about 0·01 mm. The vacuum was, therefore, about as good as that at the top of a mercury tube barometer. The complete tube was about 14 in. by 4 in. and was comparatively unwieldy.

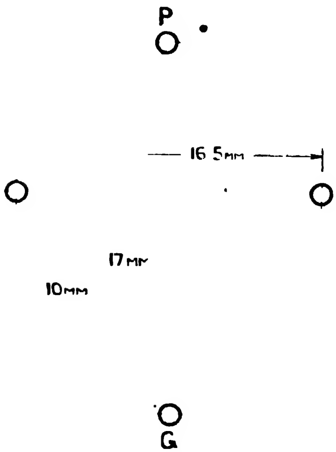


FIG. 45.—Method of arranging sockets and pins.

The "Hard" Valve.—The "soft" valves described above have proved irregular in their action and have required careful operation. Moreover, they are unsuitable for many purposes as they are unable to stand high voltages

* This form of plug was used in the original "French" valve, and is still largely used in France and Great Britain.

† *Vide* Reisz, *Electrician*, lxxii. p. 726 (1914).

on the plate. As one increases the voltage on the plate, ionisation of the gas molecules sets in; at a critical voltage, violent ionisation sets in accompanied by a bluish glow, which frequently pervades the whole tube. At the same time the plate current increases very rapidly. When this condition is reached, the valve is practically useless for any purpose. Small voltages of about 30 volts are usually used on the plates of small soft valves.

The need for a valve capable of regular operation and able to stand high potentials across its electrodes resulted in the development of the "hard" valve, that is, a bulb which has been very highly exhausted. A valve would scarcely be called hard unless the pressure inside the bulb were less than 1/10,000th mm. of mercury.

The "hard valve" is largely the outcome of investigations by I. Langmuir in the research laboratories of the G. E. C. (of U.S.A.) at Schenectady, N.Y. The "kenotron" * which has already been described, consists of two electrodes enclosed in a bulb which has been very highly exhausted. The pressure in the bulb is not less than 1/100,000th mm. of mercury. The first use of a bulb of such a high degree of exhaustion appears to be the X-ray tube invented by W. D. Coolidge in 1913.† The tube is exhausted to such a high degree that no conduction takes place through the vacuum even when voltages as high as 100,000 are placed across the electrodes. When the cathode filament is heated, however, conduction takes place in one direction only, the current consisting of a flow of electrons from the negative electrode to the positive one. Since there are practically no ionisable gas molecules in the tube, a reversal of the potential applied to the electrodes will produce no flow of current. A voltage as high as 200,000 may be used with this tube.

A development of the "kenotron" was the "pliotron," which consists of a kenotron fitted with a grid. A description of the pliotron was given before the Institute of Radio Engineers in April 1915.‡ Fig. 46 shows an early type of pliotron made by the G. E. C.

* S. Dushman, *General Electric Review*, March, 1915; also abstract in *Electrician*, lxxv. p. 276 (1915.)

† W. D. Coolidge, *Electrician*, lxxiv. p. 505 (1915); British Patent 14892/13 (June 27/13).

‡ I. Langmuir, *General Electric Review*, May, 1915; *Electrician*, lxxv. p. 240 (1915); and British Patent 15788/14 (July 1/14).

Construction of the Pliotron.—The cathode may be a tungsten, tantalum or other filament in the form of a single straight length, one or more V-shaped pieces connected in parallel, or a long piece wound to and fro on two parallel

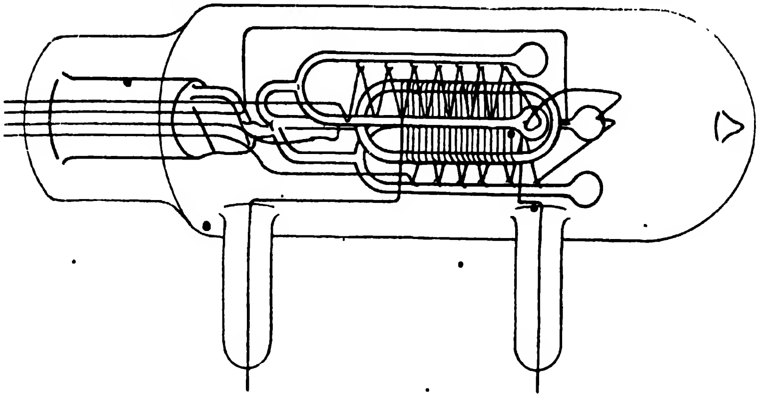


FIG. 46.—An original form of pliotron.

tungsten rods. Over the frame of glass may be wound a tungsten or other wire forming the grid. Through the centre of this frame passes the filament of the pliotron. Care is taken to prevent the filament from touching the grid. When the filament is heated, it sags and is liable to touch the grid. To prevent this, a small spring (Fig. 47) is used in many valves to keep the filament taut.

FIG. 47.—Showing grid and filament of a pliotron.

The anode of the pliotron consists of a framework of tungsten or other wire (Fig. 46) placed on each side of the grid. Instead of wires, metal plates may be placed on either side of the grid. The general arrangement is then similar to the arrangement of de Forest's audions.

The essential feature of the device is that it is an electron discharge vacuum tube in which there is no ionisation.

Methods of Exhaustion.—To obtain the high vacuum

necessary in these tubes, every precaution has to be taken. Exhaustion is usually effected by a Gaede pump,* or a special mercury condensation pump as developed by Langmuir.† As the metals constituting the electrodes absorb, or occlude, gases and are liable to liberate them when the tube is in use, thereby causing a reduction in the vacuum, every precaution is taken to get rid of these occluded gases. This is usually done during the process of exhaustion by heating the various parts to incandescence. The gases are liberated and drawn off by the pump. When the grid and anode consist of wires, it is a simple matter to heat them by passing a current through them. When they consist of plates, it is usual to heat them by electronic bombardment. For example, by passing an electron current of 80 milliamperes from a cathode to a metal plate of 2 square centimetres area and 0·01 in. thick, the bombardment of the plate by the electrons was, in a certain case, sufficient to maintain the plate at almost white heat. Chemical absorbents such as electrically vaporised calcium or magnesium, or a preparation containing red phosphorus, may be used to assist in getting rid of the occluded gases. The size of the plate should be large enough to deal with the power that will be involved, and yet should not be of such dimensions as will make it difficult to get rid of the occluded gases.

The plate is invariably subjected to a higher temperature during the process of exhaustion than it is likely to reach during the working of the valve. During the process of exhaustion the bulb is frequently blackened. In a receiving valve this is no disadvantage, but rather indicates that the electrodes have been thoroughly heated. In high-power transmitting valves the black deposit is liable to cause leakage, and special precautions, such as widely separating the connections to anode and filament, are necessary.

The following abstract ‡ of some interesting facts (given by an American manufacturer in 1917) concerning the manufacture of vacuum tubes will be of interest:

Tungsten has been found ideal as a filament, not only because of its refractory qualities and low volatility but also because it acts as a purifying agent by attacking any traces of residual gases that may remain in the tube and forming compounds which are then volatilised on the walls of the tubes.

* *Engineering*, xcvi. p. 379 (1913).
† *The Electrical Review*, lxxx. p. 41 (1917).
‡ O. B. Moorhead, *Proc. Inst. Radio Eng.*, 5, No. 6, Dec. 1917.

Various grades of glass were experimented with for use in the construction of bulbs. Grades containing a high percentage of lead and a small quantity of silicic acid were found to be the easiest to work and produced a detector of maximum sensitiveness when used in conjunction with aluminium plates and copper grids.

Aluminium plates and copper grids were selected on account of their electro-chemical relation to the tungsten filament. Other metals have been tried under the same and other conditions of exhaustion, and have shown widely different operating characteristics.* The selection of metals for the elements is very difficult, as a slight difference in either copper or aluminium changes the whole system of exhaust. This variation has been eliminated to some extent by subjecting the aluminium plates to a temperature of approximately 315° C., immersing them in a saturated solution of cyanide of potassium, and finally rinsing in alcohol. The copper is subjected to heat until it glows, when it combines with the oxygen of the air to form a black, brittle oxide, which breaks off in scales and exposes the underlying metal which is of rose-red colour. It is then placed in a current of moist air and becomes covered with a layer of oxygen compounds, which remains very thin, but closes the pores of the metal.

The filaments are heated to incandescence for two hours by means of an alternating current before fitting them into the bulb. This is to get rid of the positive ions which are usually emitted, at first, from a new filament.

To produce the necessary vacuum a Gaede mercury pump capable of producing a vacuum of 0·00001 mm., backed by a piston pump, such as the Geryck type, is most useful. The complete vacuum tube is heated gradually in an oven to a temperature of 480° C., at which the pumps are started. When the pumps have produced a vacuum of one micron (0·001 mm. or one-millionth of a metre) the temperature of the tube is very gradually increased to 540° C. At this point care must be taken, as the glass walls of the tube are liable to collapse. From one micron the vacuum slowly increases, and after about five hours of continuous pumping the tube is sealed off and allowed to cool gradually.

A more common method of exhaustion consists in placing

* Nickel anodes are almost invariably used in England and give every satisfaction. The grids are either of nickel or molybdenum

a high voltage (say 2000 volts) alternating current supply across filament and plate and utilising the electron current which flows when the plate is positive to bombard and so heat up the plate, thus liberating occluded gases.*

Functions of the Grid.—Now that we have seen some of the various methods of disposing the various electrodes in the vacuum bulb, let us consider the use of the grid and its effect on the stream of electrons passing through it (*Fig.* 39).

The chief function of the grid is to control this flow of electrons. For this reason it is sometimes termed the *control electrode*. If we place a negative charge on the grid by connecting a cell with its negative terminal to the grid and its positive terminal to the filament, the grid by its electrostatic force will repel many of the negative electrons which would otherwise have gone straight to the plate. This, of course, results in a drop in the plate current. As we increase the negative potential of the grid we will ultimately reach a point where the repellant action of the grid is sufficient to turn back *all* the electrons which would have gone to the plate. The plate current, therefore, drops to zero. The repellant force of the grid now equals the attractive force of the plate; but since the grid is only half the distance to the plate, or less, and since the grid is usually wider than the plate, a much smaller voltage on the grid is sufficient to counteract the attraction of the plate.

The author obtained with a certain valve the following values of grid potential which completely neutralised the positive potential of the plate.

Grid potential.	Plate potential.	Ratio grid potential to plate potential.
−6 v.	+33·5 v	$\frac{6}{33{\cdot}5} = \frac{1}{5{\cdot}6}$
−10 v.	+ 54 v.	$\frac{10}{54} = \frac{1}{5{\cdot}4}$
−15 v.	+82·5 v.	$\frac{15}{82{\cdot}5} = \frac{1}{5{\cdot}5}$
−18 v.	+100 v.	$\frac{18}{100} = \frac{1}{5{\cdot}5}$
−28 v.	+154 v.	$\frac{28}{154} = \frac{1}{5{\cdot}4}$

* This system is quite distinct from the preceding one. Aluminium ould melt if bombarded to the usual temperature.

This table shows that in the case of this valve, 1 volt on the grid had approximately the same effect as $5\frac{1}{2}$ volts on the plate. The grid, therefore, exercised considerable control of the plate current.

If we now try the effect of placing a positive potential on the grid, we will notice that the plate current is increased. This is partly because the grid has now *added* its attractive force to that of the plate. It helps the plate to draw up electrons which swell the plate current. These electrons attain a much higher velocity and pass through the spaces in the grid. Some of them strike the grid and cause a *grid current* to flow in the *grid circuit*. This grid current, however, is usually small. During the operation of a certain valve, when the grid attained as high a voltage as +5 volts, the grid only drew to itself about 4 per cent. of the total number of electrons on their way to the plate. The effect, however, of increasing the grid potential from zero to +5 volts was to cause the number of electrons entering the plate to increase by 150 per cent.

It will be readily seen that if we keep on increasing the positive potential of the grid, a point will soon be reached when we have assisted the plate to draw up nearly all the electrons emitted. Saturation point is therefore reached, and a further increase of grid potential will cause no increase in plate current.* The plate saturation current obtained in this manner will not, of course, be the true saturation current, and will not represent the actual electron emission from the filament. To obtain the latter value we will have to add also the current flowing to the grid.

We thus see that by simply altering the grid potential we can vary the plate current from zero to saturation value.

Effect of Grid on Space Charge.—The effectiveness of the control exercised by the grid may also be explained to a large extent by considering the effect of this electrode on the space charge existing in the tube.

Under normal conditions there is usually a space charge or atmosphere of negative sign formed by the cloud of electrons on their way to the plate. The effect of this space charge is felt most in the neighbourhood of the filament. Newly emitted electrons, if they are to reach the plate, have to

* It will, in time, actually cause a decrease since it will deflect electrons to the grid.

overcome the repulsion of the whole mass of electrons between filament and plate. Many electrons fail to overcome this repulsion and return again to the filament, unless the plate potential is high enough to overcome the effect of the space charge.

We can readily sympathise with the newly emitted electron, and understand why the space charge has such a limiting effect on the number of electrons going to the plate, and therefore on the plate current. Anything which can increase or dispel this space charge is going to have a very marked effect on the current passing through the tube. This effect is exercised by the grid. When the grid of a hard valve—and it is this type which we will be chiefly considering in these pages—is left disconnected, the electrons which strike it charge it to a negative potential, which will repel electrons leaving the neighbourhood of the filament and will increase the space charge between filament and grid. This will cause a considerable reduction in the plate current.

If the grid is connected to the negative end of the accumulator which lights the filament it may be considered as having zero potential. It will, however, be at a lower potential than the positive end of the filament and will therefore tend to repel electrons which come from that end. There will thus be formed a small space charge due to this effect, which will cause the plate current to be smaller than if the grid did not exist. There are other reasons for this fact which we will not discuss at this stage.

If we place a negative charge on the grid, the latter will repel electrons which would normally have gone to the plate. These repelled electrons collect in the space between filament and grid and constitute a strong space charge which combines itself with that of the grid to try and prevent electrons passing to the plate. The reduction in plate current consequent on the placing of a negative potential on the grid is, therefore, the result not only of the repulsion of the grid, but also of the repulsion exercised by the additional space charge produced by the negative grid potential. Hence another and very important explanation of the sensitiveness of control possessed by the grid.

When a positive potential is placed on the grid of a valve, its electrostatic effect on electrons in the neighbourhood of the filament is very considerable and it tends to neutralise the

electrostatic effect of the space charge. The result is a sudden increase in the plate current. If the grid potential is sufficiently positive it may completely neutralise the effect of the space charge. It is of value to note that the space charge is now moved into the grid-plate region. Electrons pass through the grid and collect in the space between grid and plate. If the plate is not at a sufficiently high potential to draw away all the electrons as quickly as they pass through the grid, a space charge will form in that region.

Effect of Grid on Potential Gradient.—By looking at the question from the point of view of the potential drop across the space between filament and plate, we may perhaps get a still clearer idea of the effect of the grid. Fig. 48 shows the potential gradient OGP. The distance between the various electrodes are represented by the abscissae, the ordinates representing the potentials at each electrode.* A contributing cause of the sag in the curve is the effect of the space charge. At O the electron is hardly affected by the plate and the potential gradient is practically zero. Gradually, however, the velocity of the electron increases after it has left the filament. If we place the grid close to the filament it will have a much greater accelerating effect on the electron than it would have if placed closer to the plate, where the electron would already have a very considerable velocity. The grid, by being close to the filament, is capable of a great proportional effect on the potential gradient, and therefore on the plate current.

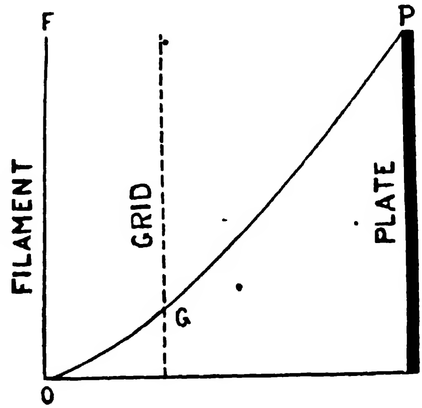


FIG. 48.—Showing potential gradient between filament and plate

The question of the proportions of the grid is important. The attractive force of the plate on an electron near the filament

* An interesting account of the potential gradients in a vacuum tube is given by Stuart Ballantine, *Proc. Inst. Radio. Eng.*, p. 145, April, 1919.

will depend largely on the spacing of the wires constituting the grid. If the wires are very close together, the grid will almost completely screen the electron from the electrostatic force of the plate. Consequently, when fine-meshed grids are used, high plate potentials are essential. If a given grid be placed too near the plate its control action will be considerably lessened. Likewise, although this is not so obvious, if the grid be too near the filament, the amplifying power of the valve will be lessened. This is because the wires of the grid will only control the velocity of the electrons immediately underneath. The electrons which leave portions of the filament not covered by the grid are practically unaffected by voltage changes on the grid which would be acting sideways to a great extent. When the grid, however, is some distance from the filament, potentials on the grid produce an evenly distributed electrostatic field which will influence all the electrons. For effective control the wires should be close together, but here we have the disadvantage of large grid currents and high anode potentials. The tendency is now towards rather open grids, and low plate voltages.

Grid-Potential—Plate-Current Characteristics.—So far our conclusions as to the effect of the grid voltage on the plate

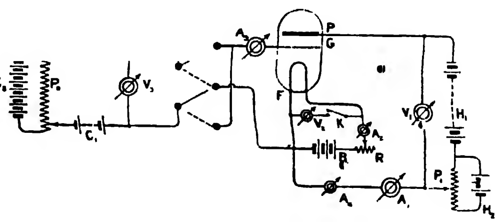


FIG. 49.—Experimental apparatus for obtaining characterist

current have been more or less theoretical. We can, however, study the effects quantitatively by arranging to measure the various quantities involved. Fig. 49 shows a practical circuit for obtaining definite results. The grid of the valve is shown as a dotted line G. The filament F is heated by an accumulator B through a variable resistance R of about 5 ohms, and an ammeter A_2 suitable for measuring currents of about 1 ampere. The potential across the filament may be measured by the voltmeter V_2 by closing the small switch K shown at the side. This switch is left open when taking the reading of A_2. The battery H_1 is the plate circuit battery variable in steps of about

15 volts up to, say, 150 volts. The potentiometer arrangement P_1 and the battery H_2 are arranged so that any required voltage measured by V_1, may be given to the plate. The plate current is measured by a milliammeter A_1 which for ordinary measurements should read up to 10 milliamps. A micro-ammeter A_4 may be included in the plate circuit, if desired, to measure the lower values of plate current.* C_1 is a battery for varying the potential of the grid. It is variable in steps of about 6 volts, but can be omitted when the potentials to be applied to the grid are small. The potentiometer arrangement C_2 and P_2 is for the fine adjustment of the grid potential which is measured by the voltmeter V_3. The commutator switch S enables us to apply either positive or negative voltages to the grid. In the figure the batteries C_2 and C_1 are opposing each other. They should preferably be arranged to act in series. The grid current, if it exists, is measured by the microammeter A_3.

Having arranged the apparatus as in Fig. 49, let us fix the voltage across the filament at 3·5 volts, and the voltage indicated by V_1 at 50 volts. The ammeter A_1 may register about 2 milliamps. If we now place a negative potential on the grid by placing the switch S in the position shown by the dotted lines, the plate current may drop to, say, 1 milliamp. By adjusting P_2 we may gradually increase the negative potential on the grid until the plate current is completely cut off. We may assume that normally the battery C_1 is omitted.

Let us now reverse the switch S and place a gradually increasing positive potential on the grid. We note two facts: the microammeter A_3 begins to show an appreciable deflection, indicating that electrons are beginning to flow to the grid; also we notice that the plate current measured by A_1 is increasing, and continues to increase up to a certain point after which the reading in A_1 remains steady, indicating that we have reached saturation point. Although the Fig. 49 circuit is very convenient, the author is inclined to prefer the arrangement in which the grid voltage battery and grid voltmeter require changing over when passing from negative to positive grid potentials. This saves the grid circuit being left open and causing a sudden change in the current through the plate circuit milliammeter. Such a change does not tend to improve the accuracy of the results.

* It is shorted when its range is exceeded

Let us now draw up a table showing the value of the plate current for different values of grid potential, starting at the potential which cuts off the plate current and working up, in steps of one volt, to the value which produces saturation.

The author gives in Fig. 50 a table of results he obtained with a small hard valve of similar dimensions to those given in connection with Fig. 42, with a constant voltage of 33·5 volts on the plate.

Plate voltage = 33·5 v.
Filament voltage = 3·5 v. (0·6 amp.).

Grid potential (volts).	Plate current (milliamp.).
− 6	0
− 5	0·02
− 4	0·10
− 3	0·20
− 2	0·35
− 1	0·55
0	0·80
+ 1	1·05
+ 2	1·30
+ 3	1·51
+ 4	1·74
+ 5	1·92
+ 6	2·09
+ 7	2·20
+ 8	2·29
+ 9	2·31
+ 10	2·35
+ 11	2·37
+ 12	2·39
+ 13	2·39

FIG. 50.—Table showing effect of grid potential on plate current.

These results may most conveniently be represented by a curve drawn on sectional paper as shown in Fig. 51.

It will be seen that there are two bends in the curve, one at A and one at B. The one at A is due to the effect of the space-charge, which decreases as the potential of the grid rises, and the one at B is due to the effect of saturation. Neither bend, it is to be noted, is particularly sharp. The portion of the curve between A and B is steep and approximately straight. From this we can deduce two facts:—

(*a*) Small variations of grid potential will cause large variations of plate current.

(b) Since the curve along this portion is straight any variation of grid potential will cause proportional variations in the plate current.

From the curve we see that under normal conditions, when the grid is at zero volts, the plate current is 0·8 milliamp. By putting a gradually increasing positive voltage on the grid we cause very considerable increases in the plate current until, at about +12 volts, the plate current reaches a maximum value and remains constant at about 2·4 milliamps. If, on the other hand, we put a negative charge on the grid, we reduce the plate current. By gradually increasing the negative charge on the grid we will ultimately cut off the plate current altogether. This, as will be seen from the curve, takes place at about −6 volts.

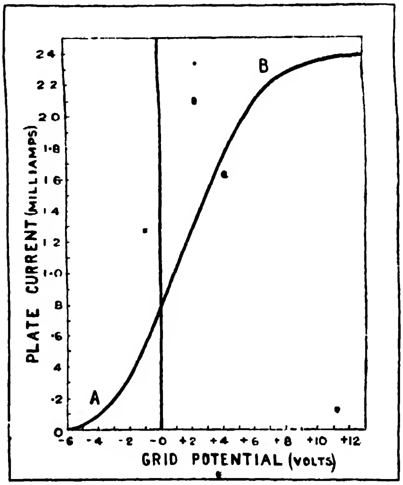


FIG. 51. Grid voltage-plate current curve of a typical hard vacuum tube.

Simple Amplification Circuit.—The reader will no doubt have realised by now the possibilities of the valve as a magnifier, since small variations of grid potential will cause large variations of plate current. Let us connect up a circuit similar to that of Fig. 52, where A is a source of alternating current. The grid circuit is shown by the letters GAJF, and the plate circuit by PHTJF, where T are telephone receivers.

We will suppose the valve is working under the conditions shown in the graph of Fig. 51. The grid is obviously at zero potential since it is connected, *via* A, to the negative end of the filament. The plate current passing through the telephones T will, therefore, be 0·8 milliamp. This steady current will produce no sound.

When, however, the alternating potentials supplied by A are imposed on the grid the plate current rises and falls above and below its normal value. If the potential of the grid is

made to vary from +1 volt to —1 volt, the plate current will first rise from 0·8 milliamp. to 1·05, then fall to 0·8, then drop to 0·55 and at the end of the alternation rise again to its normal value. It is to be noted that the increase of plate current, 0·25 milliamp., is equal to the decrease. We have, therefore, produced alternations in the *plate circuit of exactly* the same nature as those impressed on the grid. Moreover, the plate circuit alternations are much stronger than those taking place in the grid circuit. They have been *amplified*. In addition they keep time exactly with the grid circuit alternations, since the inertia of the stream of electrons is negligible.

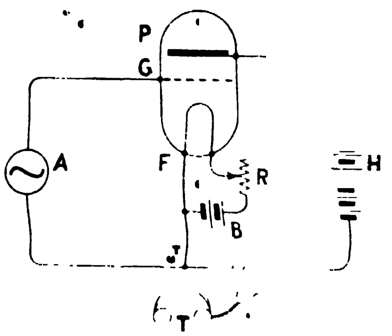


FIG. 52. Simple amplifier circuit.

If the alternations applied to the grid are of a frequency less than about 7000 per second the variations of plate current will produce a buzz in the telephone receivers T, which will produce a click for each increase or decrease of plate current. These increases and decreases are shown clearly in Fig. 53. The dotted line represents the normal plate current. If the alternations have a frequency exceeding about 7000, practically nothing will be heard in the 'phones, which are incapable of responding to a frequency much higher than this. Moreover, the human ear is incapable of hearing clicks at a greater frequency than about 14,000 per second. Actually, it can only hear efficiently frequencies less than about 3000.

FIG. 53.—Effect on steady plate current of an alternating voltage on the grid.

In Fig. 52 we have considered the grid to be at zero potential. If we had placed a steady potential of —3 volts on the grid by means of cells included in the grid circuit, or by any other means, we would have been working our valve

on the lower bend of the curve as shown in Fig. 51. The normal plate current will be 0·2 milliamp. A positive potential of 1 volt impressed on the grid will cause the latter to assume a potential of —2 volts, causing the plate current to increase to 0·35 milliamp. The negative half-alternation will cause the grid potential to drop to —4 volts, for which value the plate current will be 0·1 milliamp. It will therefore be seen that positive half-cycles cause an increase of 0·15 milliamp., while negative half-cycles cause a drop of only 0·10 milliamp. The average effect of one alternation on the grid has been to cause an increase in the plate current. Our original alternation has been rectified to a certain extent, and we can no longer say that the variations of plate current are similar to the variations of grid potential. We, therefore, must take care that the grid potential is such that the variations of plate current around the normal value are symmetrical. If we arranged the grid potential to be +8 volts we would still have rectification, but this time the average result of one alternation would be a decrease in the plate current, since we are working on the saturation bend.

We naturally come to the conclusion that only the straight portion of the curve should be used when amplifying. On the steepness of the grid-potential—plate-current curve depends largely the degree of amplification it is possible to obtain with a valve. The steeper the curve the greater will be the amplification obtained. The degree of amplification is roughly proportional to the tangent of the angle made by the curve with the horizontal axis at the point of operation. It will vary with different positions of the representative point, but usually remains fairly constant along the steep straight portion of the curve.

Further details of the operating characteristics of the valve as an amplifier are given in the paragraph dealing with characteristic curves, and practical circuits are shown in the next chapter.

Simple Rectification Circuit.—We noted, while discussing the amplifier circuit of Fig. 52, that when the normal grid potential was of such a value that its ordinate cut the curve at a bend, symmetrical amplification was not obtained. This suggests to us the use of the vacuum tube as a rectifier of wireless oscillations. All that we have to do is to adjust the potential of the grid so that the valve is being worked at the

lower or upper bend. Moreover, this rectification will be accompanied by an amplification effect which will produce signals of much greater strength than those obtained on a two-electrode valve.

In Fig. 54 we have a simple circuit utilising the three-electrode vacuum tube as a detector. P_2 and E constitute a potentiometer arrangement for adjusting the grid potential to a point on one of the bends of the characteristic curve. The sliding contact shown by an arrow-head is capable of moving along the whole length of the potentiometer resistance.

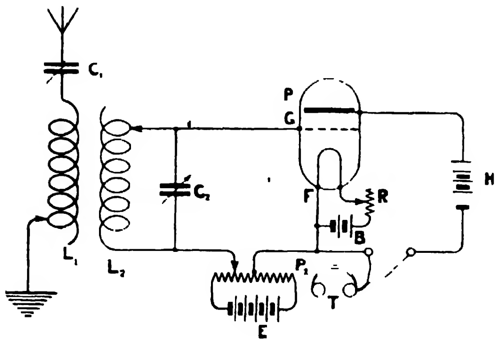


FIG. 54.—Receiving circuit in which rectification is obtained by using one of the bends on the plate current curve.

This resistance may conveniently consist of a rod of graphite taken from an ordinary lead pencil; such a resistance has the advantage of being non-inductive.* The rectified oscillations produce signals in the telephone receivers T.

One of the advantages of the valve as a detector is that it requires very little energy to operate it, since the capacity of the grid is very small and since the resistance of the space between filament and grid is very high. When the grid remains negative during the reception of signals, the resistance of the space is almost infinite and no damping of the wave trains is traceable to the valve. Even if the grid is positive during the operation of the valve, the grid current formed is very small and the resistance of the space between filament and grid is in the neighbourhood of 100,000 ohms.

It must not be assumed that rectification can only be obtained by using one of the bends of the curve. There are several methods by which it is obtained, and these will be discussed in the following chapter.

Let us now look more closely into the operation of the valve

* A potentiometer having a resistance of about 400 ohms is usually used in practice.

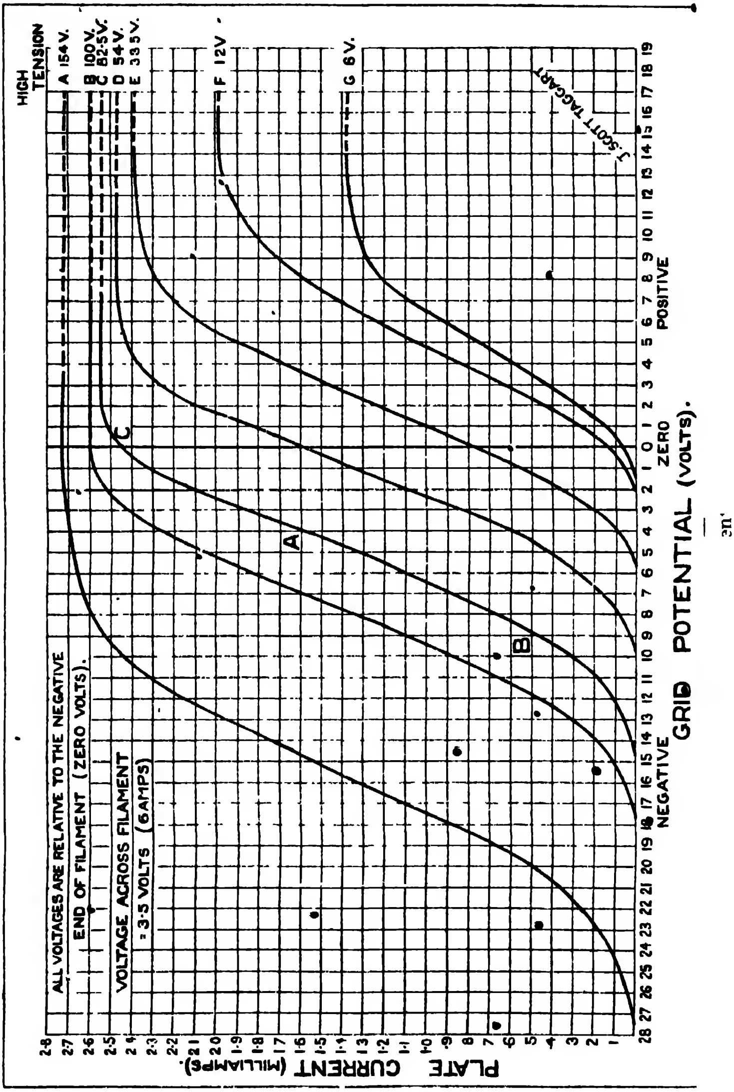
under varying conditions and see what information may be obtained by a study of a number of characteristic curves.

Further Notes on the Characteristics of the Three-Electrode Tube.—In Fig. 51 we gave an example of one of the curves obtained by keeping the plate voltage and filament current constant and varying the grid potential. In Fig. 55 the author gives a number of curves he obtained with a small hard valve having a widely-spaced grid. These curves may be considered typical of all hard valves.

Not only is the 33·5 volt curve given, but also several more tained by using different voltages on the plate, but keeping the voltage across the filament at olts. Let us look first at the curve obtained when 33·5 volts are on the plate. From this we see that under normal conditions the plate current is 0·8 milliamp. By putting a gradually increasing positive voltage on the grid we cause very considerable increases in the plate current until, at about +13 volts, the plate current reaches a maximum value, and remains constant at about 2·4 milliamps. If, on the other hand, we put a negative charge on the grid, we reduce the plate current. By gradually increasing the negative charge on the grid we will ultimately cut off the plate current altogether. This, as will be seen from the curve, takes place at about −6 volts. The effect of putting a higher voltage on the plate is to extend the height of the curve until it reaches a certain maximum height, and also to displace the characteristic curve to the left, as will be seen from such examples as the 54 volt, 82·5 volt and 100 volt curves. The curves are still approximately of the same shape and maximum steepness at the different plate voltages given.

It will be noticed also that as we reach the higher plate voltages the value of the saturation current almost ceases to increase. This is to be expected, since the real saturation point of the valve is being reached when all the electrons emitted from the filament go to the plate. In the case of those curves which lie partly to the right of the vertical line through zero grid voltage, which in future we will call the grid zero ordinate, the grid is given a positive charge. It is the resulting flow of electrons to the grid and the establishment of a grid current which chiefly prevents the 6-volt curve from reaching the same height as the 154-volt curve. If we added together the values of the grid current and the plate current at the saturation point of the 6-volt curve we would find that the

total was approximately the same as the maximum current obtained on the 154-volt curve.



It will be clearly seen that by taking any of the curves of Fig. 55, and by suitably adjusting the voltage on the grid, we

can use the valve at any point on its characteristic curve. When we speak of using the valve at a certain point on its curve we mean that the vertical line through the given grid voltage cuts the curve at that point.

Take, for example, the 82·5-volt curve. With no volts on the grid the valve is functioning almost at its saturation point; at -5 volts the valve is working at a point midway along the straight steep portion of its curve; at -12 volts the valve is being used at the bottom bend of its curve. It will be seen later that it is of the utmost importance that we should be able to adjust the valve to that point on its characteristic curve at which it best carries out the function desired of it.

The same object may be achieved by varying the high-tension voltage, varying the filament current, and by varying the two together. Let us first see the effect of varying the *high-tension* or plate voltage, keeping the grid voltage constant, say, for example, at zero volts. By placing 6 volts on the anode we are using the valve at the bottom of its characteristic curve. By placing 54 volts on the plate the valve is functioning at about the halfway point along its curve for that voltage. By increasing the plate voltage to about 82 volts the valve is functioning near saturation point.

Let us now see the effect of putting a fixed voltage on the anode, say 33·5 volts, and varying the filament current. By drawing a characteristic curve for each value of filament current we obtain the results shown in Fig. 56. They show us that by increasing the rate of electron emission we greatly extend the height of the curve, without actually displacing it bodily to one side as was the case when we varied the anode voltage. It will be noticed that all the curves have their lower portions in common, or practically so.

Although the curve is not actually displaced to one side on increasing the filament current, yet the effect is almost the same as if it were moved to the right. By keeping the grid at zero voltage and using 3 volts across the filament, we are making the valve function at its saturation point. If we increase the voltage to $3\frac{1}{2}$ volts, we will be using the valve on the straight portion of its curve. If, now, we make the potential difference across the filament 4 volts or $4\frac{1}{2}$ volts, we will be using the valve at the bottom end of its characteristic curve. We see, then, from the four curves given, that, by having a rheostat to vary the filament current gradually, we can produce curves

of any height within limits, and also arrange to have the valve functioning at any point without having to vary the grid voltage.

By having a variable filament current and anode battery we can produce almost any kind of curve, and displace it to either side of the grid zero ordinate to serve our special purpose.

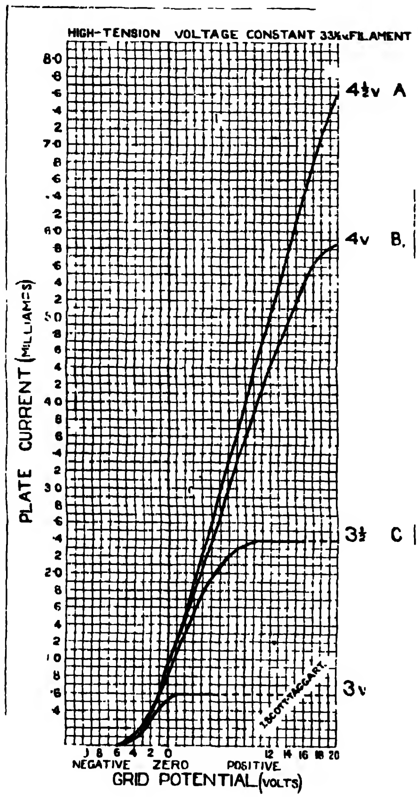


FIG. 56.—A set of characteristic curves connecting grid voltage and plate current, showing effect of varying the filament current.

Supposing, for example, we require to reproduce the 82·5-volt curve of Fig. 55 on a much larger scale: if we increase the high-tension voltage, we make the curve very little longer and also displace it to the left; if we keep the 82·5 volts constant, and increase the filament current, we will certainly increase the height of the curve, but at the same time we have done what is equivalent to displacing the curve to the right. The zero ordinate would cut such a curve about halfway up instead of near its saturation point. What we do, therefore, is to increase the height of the curve by using a higher value of filament current, and then displace it to the left into the desired position, which is completely to the left of the zero ordinate, by using a higher value of high-tension voltage. This increase of voltage also adds to the height of the curve.

Fig. 57 shows the original curve, and also a similarly placed

but larger curve obtained by correctly balancing suitable values of filament current and high-tension voltage.

From the above we see that, by judicious adjustment of filament current and plate voltage, we can vary the nature of the characteristic curve and arrange to have it completely to the left of the zero ordinate, almost completely to the right, or at any intermediate position. We have also seen that once we have obtained the desired curve by means of these adjustments, no matter what its position or height, we can use the valve at any point on that curve by adjusting the normal grid voltage to the necessary value. Thus, if we desired to work the valve at saturation point, and we have $3\frac{1}{2}$ volts across the filament and 6 volts on the plate, we would have to give the grid a normal positive potential of +11 volts. If, on the other hand, we have 154 volts on the plate, we would require a negative potential of —7 volts on the grid to make the valve function near its saturation point.

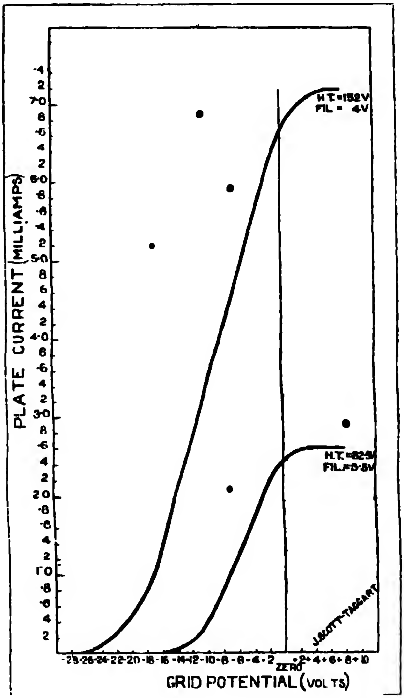


FIG. 57.—Showing how similar but larger curves may be obtained by simultaneously increasing the filament current and plate voltage.

Let us now examine the curves with a view to finding out what curve, and what point on it, is the most suitable when we desire to use the valve as an amplifier.

AMPLIFICATION.

The valve may be used as an amplifier of alternating or oscillating currents, microphonic currents produced by speech,

or intermittent unidirectional pulses. It is proposed to look more closely into the question of amplification from a quantitative as well as qualitative standpoint.

Fig. 58 shows a suitable circuit for low-frequency amplification. The potentiometer enables us to give the grid a normal potential on either side of zero. The voltage of the original alternating current is stepped up by means of a transformer before influencing the grid, its final value, let us suppose, ranging from +3 volts to −3 volts.

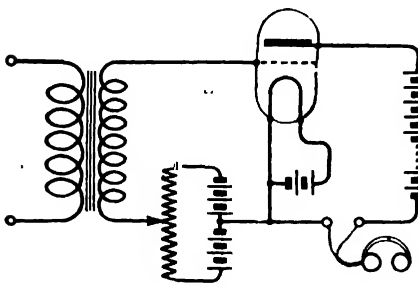


FIG. 58.—A simple amplifier circuit.

Let us also suppose that we are using our valve under conditions that give a characteristic curve similar to the E curve of Fig. 55. This curve is obtained by placing $3\frac{1}{2}$ volts across the filament and 33·5 volts on the plate.

If we keep the grid voltage zero, the negative half of each alternation will cause the grid voltage gradually to drop to —3 volts, and then to return to its normal potential. As the positive voltage builds up on the grid—due to the positive half of each alternation—a grid current will be set up, since the grid is at a higher potential than a portion of the filament. This flow of negative electrons will tend to neutralise the positive charge that the positive half-cycle is trying to place on the grid. In other words, the grid current prevents to a certain extent the rise of grid potential, just as the external voltage of a cell drops on completing the outer circuit. The result is that the positive half-cycle causes an increase in the place current, which is rather smaller than the decrease produced by the negative half-cycle.

By using the grid at zero voltage we have produced alternations in the anode circuit of a different nature to the original alterations. We have, in fact, rectified the latter to a certain extent. Since we are trying to reproduce faithfully our original current variations, this rectification effect due to a grid current is a very decided disadvantage. Moreover, it will exist in all cases where there is a tendency towards the

establishment of a grid current. If we use a higher value of anode voltage, the grid current for 3 volts on the grid is less than before, and the rectification effect is not so marked. It will always exist, however, whenever the grid potential tends to acquire a positive value, and the resultant damping effect is undesirable.

In order, then, to avoid a grid current we must never allow the grid voltage to become positive. If, therefore, we give the grid an initial potential of —4 volts by means of the potentiometer, the alternating current will vary the grid voltage between —1 volt and —7 volts. Although we now get no complications due to a grid current, by continuing to use the same curve we are still at an unsuitable point for amplification. We are using the bottom bend of the characteristic curve, and, therefore, the increase in the plate current due to the positive half of an alternation or oscillation will be greater than the decrease produced by the negative half. In our special case the increase will be 0·45 milliamp., and the decrease 0·1 milliamp. We, therefore, still have undesired rectification effects. If we increase the high-tension voltage to 100 volts we will be using a new curve, but this time the —4 volts on the grid brings us to the *upper* bend of the curve, near saturation point. At this point the positive half-cycle produces practically no increase in the anode current, while the negative half-cycle causes a very considerable drop. This time the 3 volts bring the grid voltage to —1 volt, but the plate current is only increased from 2·27 milliamps. to 2·58 milliamps., while —3 volts added to the existing —4 volts on the grid cause the plate current to drop from 2·27 miliamps. to 1·6 milliamps.

It is, therefore, important that we should avoid either of these bends. In fact, if we wish to reproduce current variations with absolute accuracy, it is essential to use straight portions of the characteristic curve. The *steep*, straight portion is obviously the part to use, since we get big current variations in the plate circuit for small grid voltage changes. Even if the ordinate passing through the normal negative grid voltage cuts a bend in the characteristic curve, the valve will reproduce fairly accurately current variations *of very small voltage*, but the amplification obtained is small.

From the above it is apparent that, to avoid rectification effects and to obtain the maximum amplification, we must use

the steep, straight portion of a curve. We could use the 82·5-volt curve and, by putting a normal voltage of —5 volts on the grid, use it approximately at its halfway point. Equal positive and negative voltages will now cause equal increases and decreases of plate current, and all current variations in

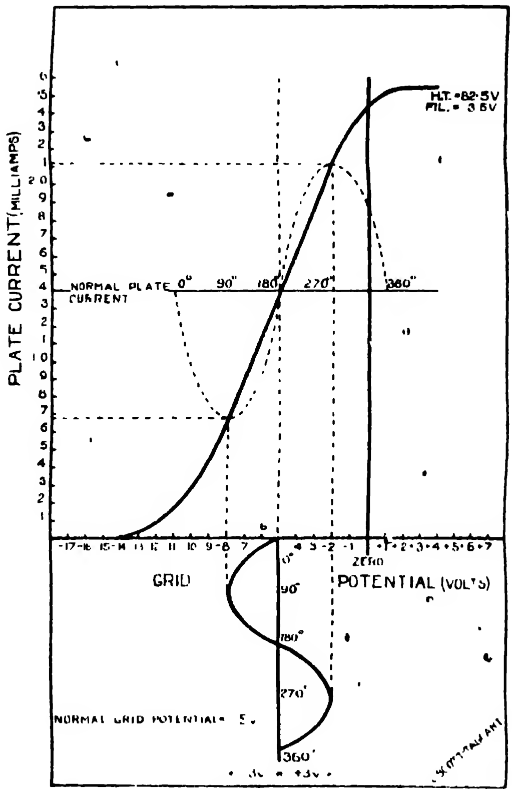


FIG. 59.—Showing graphically the amplification of a complete cycle of alternating current.

the grid circuit will be reproduced on a larger scale without distortion in the anode circuit. Fig. 59 shows the effect of a complete cycle of alternating current of 3 volts amplitude in the grid circuit on the current in the plate circuit, which is shown by a dotted line. Fig. 60 shows us the same results in a different form.

It will be seen from a study of the 82·5-volt curve under discussion that if we use a stronger alternating current in the grid circuit than the one we have so far considered, not only will we be using both bends of the curve, and so produce distortion in our anode circuit alternations, but we will not be getting the fullest amplification possible with the vacuum tube.

Let us suppose that the alternations in the grid circuit have an E.M.F. varying from —8 volts to +8 volts. By giving the grid a normal potential of —5 volts we will vary its voltage between —13 and just under +3 volts. The effect of this on the anode current is shown in Fig. 61, which shows us the distortion effects, and also shows that the amplified alternations are of not much greater amplitude than those produced by the 3-volt alternations.

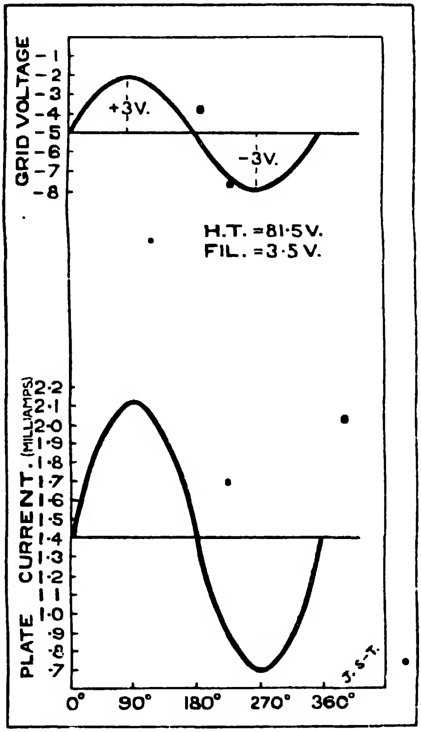


FIG. 60.—Another method of showing the symmetrical amplification of a cycle of alternating current.

From this we see that for a given characteristic curve, or, more simply, for a given value of filament current and plate voltage, the maximum amplification obtainable is limited, and is achieved when the varying grid voltage varies the anode current between zero and its saturation value.*

For strong alternations or signals, it is therefore desirable

* This phenomenon is very useful when it is desired to lessen the effect of very strong signals. The vacuum tube is a natural "limiter" and may be arranged so that strong undesired signals are amplified to a less extent than weak ones.

to extend the curve vertically. This, we have shown, can be done by increasing the filament current and high-tension voltage. We still, of course, keep the whole of the straight portion of the curve to the left of the grid zero ordinate. Fig. 59 shows the original 82·5-volt curve—which was only suitable for alternations or oscillations not exceeding 3 volts amplitude, and also a higher curve suitable for amplifying stronger current variations. This curve will do justice to our 8-volt alternations, and no distortion effects will be produced. It will, however, be necessary to give the grid a normal voltage of -8 volts in order to use the curve at its half-way point.

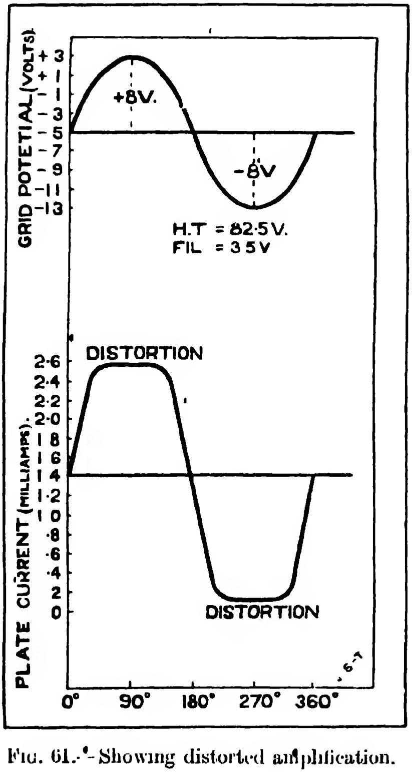


FIG. 61.—Showing distorted amplification.

Although it is not absolutely necessary to use the valve near the mid-way point along its curve, this is generally done when amplifying alternating, oscillating or microphonic currents. If the current variations are not too strong, we may use practically any point on the straight portion of the curve as our normal adjustment. The point B on the 82·5-volt curve (Fig. 55), obtained by using a normal grid voltage of -9 volts, would be quite suitable when amplifying currents which varied the grid potential 1 volt to either side of its normal value. On the other hand, it would be quite unsuitable for amplifying currents which would increase and decrease the grid voltage by 3 volts.

Thus we see that our choice of the most efficient curve and

the most efficient point on that curve is dependent very largely on the *strength* of the alternations, oscillations or microphonic currents which are to influence the grid.

The amplification of unidirectional pulses, such as are obtained from a rectifying detector, is a much simpler matter. Since the current flow is always in the same direction, we can arrange matters so that the grid always receives a negative charge at each pulse. Since there will never be a grid current, it is unnecessary to have an initial negative voltage on the grid; we can keep the grid at zero voltage and dispense with the potentiometer. As regards curves, we can use most of those given in Fig. 55, the choice depending upon the strength of the pulses on the grid. The 6-volt curve, however, is inefficient, partly because it would be unsuitable for any but very weak pulses, and partly because even then the current changes in the plate circuit would be very small, the curve gradient at this point not being steep.

The 33·5-volt curve is capable of dealing efficiently with stronger pulses which would cause the grid potential to drop to values as low as —3 volts. For still stronger pulses the 82·5-volt curve would be suitable. For pulses which would cause the potential of the grid to drop 12 volts but not more, the 100-volt curve could be used. Curves such as the 154-volt curve are practically useless for amplification,* since it would take the first 12 volts on the grid to round the saturation bend and produce a drop in plate current of only 0·6 milliamp. None of the curves of Fig. 55 would, therefore, be suitable for amplifying very strong pulses. The large curve of Fig. 57, however, would be very suitable. This curve is obtained by 152 volts on the plate and 4 volts across the filament. This curve would be suitable for *any* grid voltages down to —18 volts, which value would produce a drop in plate current of about 6 milliamps.

If, by mistake, we connected the amplifying valve or valves so that the pulses gave the grid a positive value, we would have to adjust the high-tension voltage and the filament current so that a considerable portion of the curve would be to the right of the grid zero ordinate. The 12-volt curve of Fig. 55 would be suitable. Such an arrangement might be considered economical, since the plate current is normally very small when signals are not being received. However, the amplification

* Unless, of course, a steady normal negative potential were given to the grid.

obtained is not as great as that given by the reverse connections, for two reasons closely allied. In the first place, the "straight" portions of curves become less steep to the right of the grid zero ordinate, owing to a certain proportion of electrons passing to the grid; secondly, this grid current prevents the potential of the grid reaching its full positive value. Consequently, the operating potential on the grid should never be positive.

When connecting up an amplifying valve or multi-valve amplifier, the reverse connections to grid and filament should, therefore, also be tried, and the optimum signal strengths obtained in each case noted and compared.

It will have been noticed that when we are dealing with unidirectional pulses it is not necessary to make the valve function near its midway point.

In fact, if we do this, we will be using a curve twice as high as is necessary and half the curve will never be used. This means that we are needlessly wasting current from the lighting accumulators, and perhaps from the high-tension battery. If the grid is connected so as always to receive pulses which give it a negative charge, a curve of half the height may be used, provided we use it at the upper end of its straight portion. Such a curve is the "D" curve of Fig. 56. This arrangement is almost as efficient and far more economical than using a higher curve like the "C" curve of Fig. 56. Similarly, when we arrange for the grid always to receive positive pulses, we should, for reasons of economy, use the bottom part of the steep, straight portion of the curve. The 12-volt curve of Fig. 55 would be suitable.*

For a valve to be efficient as an amplifier of any type of current variations its characteristic curve should, along its straight portion, be as steep as possible. It is important to notice that for a given valve the portions of the curves *used*—namely, the steep, straight portions of curves lying mostly or altogether to the left of the grid zero ordinate—have all approximately the same gradient. The 100-volt curve of Fig. 55 is not quite as steep as the 54-volt curve, but the variations of gradient are never considerable. If anything,

* The above remarks assume that the normal grid potential is near zero. We could with considerable advantage use a curve lying to the left of the grid zero ordinate by giving the grid a large negative potential In this case the potentials requiring amplification could be applied to the grid in a direction tending to make it positive.

the higher curves obtained by large values of filament current and high-tension voltage are the steepest.

Different types of valves, however, vary considerably in the gradient of their curves, and, therefore, in their value as amplifiers. Fig. 62 shows a comparison of the curves of two types of valves, the one having a steeper curve than the other.

Before passing on, let us summarise some of the points already dealt with above.

Different combinations of filament current and high-tension voltage give us curves of different sizes and positions. The position of the point of intersection where the curve is cut by the vertical line passing through zero grid volts, and which has been termed the grid zero ordinate, is of the utmost importance. For general amplifier work this line should cut the curve just below the saturation bend. The workable portion—the straight part—is then entirely to the left of the vertical line, and no rectification effects are obtained through the establishment of a grid current.

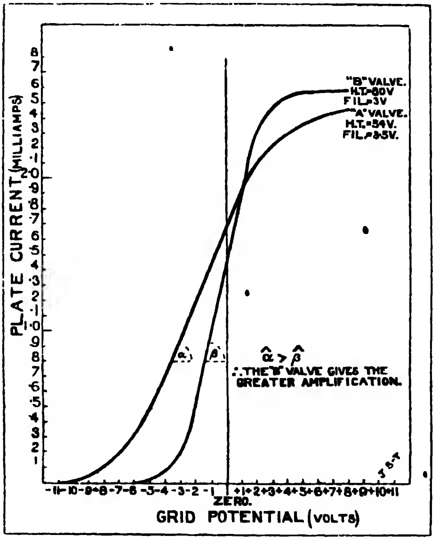


FIG. 62.—Comparative steepness of two curves.

Even more important than the curve's position relative to the zero ordinate is the point at which we work the valve—that is to say, the part of the curve cut by the vertical line passing through the normal potential of the grid, which may be given any value. To find the value of this normal grid voltage most suitable for amplifying currents of an alternating nature we have only to drop a perpendicular line from the midway point along the straight portion of our curve on to the grid voltage abscissa. This negative value may be given the grid by means of a potentiometer included in the grid circuit, no matter whether the grid circuit has in it the secondary

of a step-up transformer or an inductance coil. Where a certain amount of distortion in the amplified current variations is not of consequence we can keep the grid at zero voltage by simply connecting it through the transformer or inductance coil to the negative end of the filament. In this case we would arrange the curve so that the grid zero ordinate would cut it at its halfway point. When speech, however, is to be amplified, it is of great importance that we should avoid the slightest distortion. In practice. we could use a couple of dry cells, instead of a potentiometer, to keep the grid at normal negative value, and arrange our curves accordingly.

The characteristic curve may be displaced to the left by increasing the high-tension voltage on the anode. This hardly affects the steepness of the straight portions of the curves, which remains more or less the same for different values. It will be noticed that the curves of Fig. 55 all have their straight portions almost parallel. At the same time, the maximum height of the curve is usually increased.

The extension of a characteristic curve is practically equivalent to moving the curve to the right. The effect is to make the grid zero ordinate cut through a relatively lower point of the curve. For low values of anode voltage the extension of the curve by increasing the voltage on the plate exceeds the actual displacement of the curve to the left. The resultant effect is that the grid zero ordinate cuts through a lower relative point on the curve. As we increase the high-tension voltage the extension produced becomes small compared to the displacement to the left, so that the resultant effect is that the point where the ordinate cuts the curve moves higher and higher until saturation point is reached. The above will be more clearly understood by a reference to Fig. 55.

The effect of increasing the filament current is simply to extend the curve without actually moving it sideways. This extension, however, is equivalent to moving the curve to the right, since it causes the zero ordinate to cut it at a lower point.

By increasing or decreasing the filament current and anode voltage together we can produce a series of curves all similarly placed with regard to the zero ordinate, but of different sizes, the larger curves being suitable for amplifying very strong current variations.

Before passing on it would be as well to point out that the results given here in graphical form have been obtained by

giving the grid steady, *maintained* potentials. They may be termed the static characteristics of the valve. In actual practice, especially when amplifying high-frequency oscillations, the potentials given to the grid are only momentary, lasting perhaps for only a millionth of a second. Deductions from the curves must be made with this always in mind, particularly when considering those portions of curves which lie to the right of the grid zero ordinate. This point will be subsequently emphasised more strongly.

CHAPTER III.

THE VACUUM TUBE AS A DETECTOR.

Methods of Rectifying Oscillations.—The three-electrode (or "triode") vacuum tube may be used as a detector of wireless oscillations by taking advantage of:

(*a*) the non-linear characteristics of the grid-potential—plate-current curve;

(*b*) the establishment of grid currents;

(*c*) combinations of the above;

(*d*) the cumulative rectification effect of a grid condenser.

Use of Asymmetry of Plate-current Curve.—Let us first deal with the rectification obtained by using variations in gradient of the curve which represents the effect of grid potential on plate current. This curve is usually similar in shape to the letter S. In order to avoid the complications of other effects, such as the establishment of grid currents, we must shift our curve completely to the left of the grid zero ordinate, where we can analyse it in comfort. This moving of the curve is easily accomplished by placing a high potential on the anode, or by decreasing the filament current.

The upper curve of Fig. 63 is a very typical one. It shows a curve obtained by using a plate potential of 176 volts, and 3·5 volts across the filament. The grid potential was varied between −29 volts and zero volts, and at each adjustment the loudness of signals from an external transmitting station was noted on a circuit similar to that of Fig. 64. which is self-explanatory. Comments have been made at different points on the curve, showing how the loudness of signals varied, and it will be seen how closely the actual results obtained bear out the conclusions we made.

At about −29 volts the signals are very weak because the curve at this point is only beginning and slopes upwards very gradually. This adjustment O (Fig. 75) may be termed the

point of origin, and is most unsuitable, particularly for the detection of weak signals. The rectification effect is good,

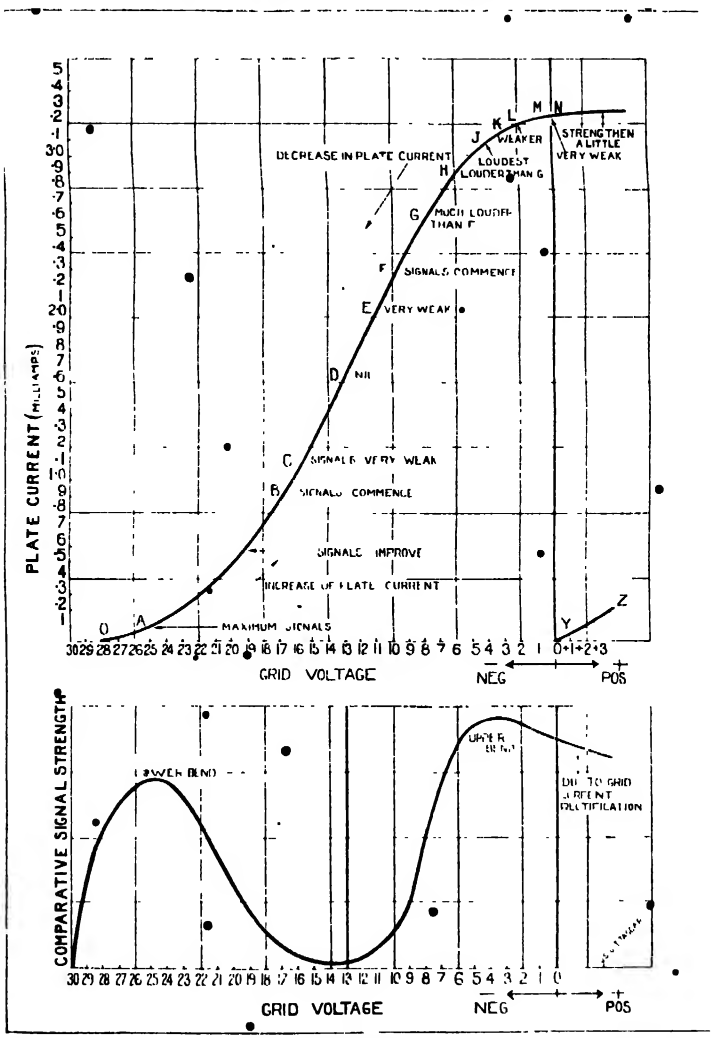


FIG. 63.—Demonstrating rectification obtained through asymmetry of plate current curve.

since negative half-oscillations produce absolutely no plate current while positive half-cycles *do* produce a current, but

this is so very small that the *amplification* effect is negligible. The signal strength, it must be remembered, depends not only on the degree of rectification but also the amplification.

As we decrease the negative potential of the grid signals become louder, since the curve steepens. At A we obtain the loudest signals on the lower bend of the curve. When incoming oscillations are strong it is hard to define the best operating point. Any part of the lower bend can usually be used with equal effectiveness. When signals are very weak the adjustment is more critical and one cannot say definitely

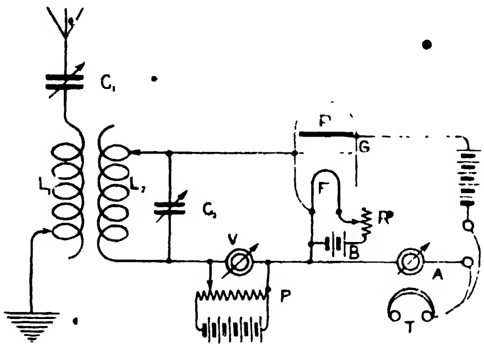


FIG. 64.—Circuit for studying the rectification obtained on plate current curve.

by *looking at the curve* what point will be most suitable. The point most students would select would probably be higher than the one which would give best results in practice. Very fine adjustment is not usually required, since it is a bad principle to apply weak oscillations to a valve rectifier; oscillations should be first magnified by one of the various means available.

As we move our operating point further up the curve, the signals die off gradually and disappear very rapidly after the point B, where we begin to enter on to the straight, steep portion of the curve. The oscillations are now producing large current variations, but the rectification has become negligible. At D it is absolutely zero, and we note that D is very approximately the halfway point along the curve. The point D is therefore ideal for the faithful reproduction on a magnified scale of any current variations we may desire to amplify.

As we decrease the negative potential of the grid, the operating point will move higher up the curve. At E very weak signals are heard, which become more appreciable at F owing to the convexity of the curve. The plate current now drops slightly during the reception of waves from an external station. At G signals become much louder, and at J they reach a maximum. This point J is what the author has previously termed the initial point of saturation. It is, as it were, the brink of the curve. Below, the curve makes a steep descent. Above, it gradually rounds off until at M it becomes level.

It is this initial point of saturation which is usually the best adjustment. In many valves it is superior to the point A at the lower bend. This is particularly the case in the RV30 valve, whose curve at saturation point is very sharp. The reason for the efficiency of the point J is not far to seek. Since it is the brink of the curve, a small additional negative potential will carry the representative point a considerable distance down towards H. An equal increase of potential above the normal value of the grid (—4 volts) will, however, cause the representative point to move only a little higher up the slope. The result of an oscillation is a considerable average drop in the anode current. Good rectification can always be obtained if the vertical line, or ordinate, through the normal grid voltage cuts the curve, or *characteristic surface*, at a point where the curve is convex or concave. Better rectification can be obtained if the curvature changes rapidly. If the curve being used is a parabola the exact operating point is immaterial. The rectification at any point is the same. If, however, our curve is a parabola up to a certain point and then suddenly becomes very much steeper, the curvature will have changed, and the best operating point will be where the curve changes. Such critical points are frequently met with in vacuum tube work, although not enough attention is given to the rectification due to a uniform curve.

As the operating point on our (Fig. 63) curve is moved further up, the signals obtained become weaker, as at K. At L, which might have been thought the best point, signals are still weaker although good. The bend is pronounced, but, although the increases of anode current for positive half-oscillations is almost negligible, this is counterbalanced by

the fact that for negative half-oscillations the representative point only travels on a gradual curve and the drop in anode current, though greater than the increase, is still only small. This point, however, is an excellent adjustment when incoming oscillations are strong, and sometimes proves more efficient even than J. The representative point will now travel a considerable distance down the straight steep portion of the curve when negative half-oscillations influence the grid.

At M, the final point of saturation, the curve becomes level and further positive grid voltages cause very little difference. With —1 volt on the grid we have reached conditions analogous to those existing at O. Rectification is good, but weak oscillations produce practically no results since the curve to the left of M slopes down only very gradually, and the amplification effect is very small indeed.

At N (zero grid volts), signals begin to improve a little and do not die down to zero as we might have thought at first. This is due to a very interesting effect produced by the establishment of a very weak grid-current. This effect is discussed later, but a few remarks to explain the phenomenon will not be out of place here. When the grid potential becomes positive the grid draws to itself a number of electrons. The higher the positive potential of the grid the greater will be the grid current. A curve YZ (Fig. 63) may be drawn to show the grid-current for positive potentials of the grid. It may, for the time being, be considered as starting at zero volts. Any positive potential on the grid caused by positive half-cycles will make the grid potential higher than that of a small portion of the filament measured from the negative end. The resultant electron-current will tend to prevent the positive charge on the grid building up, thus partially damping out the positive half-cycle. The positive half-oscillation will therefore cause a smaller change in *grid potential* than the negative half-cycle. It will, of course, be realised by the reader that when 176 volts are being used on the anode the grid current will be infinitesimal since the anode will be capable of drawing almost all the electrons *through* the grid even if some did wish to go to it.

Now, if the curve at N were absolutely level, no variation of grid potential would produce any effect. As a matter of fact, however, the curve is usually a very slight gradient upwards, due perhaps to the effect of the grid on what little might remain of the space charge and on the few " reluctant "

electrons. On the other hand, the curve may be sloping gradually downwards since the grid is beginning to rob the anode of its electrons by diverting them to itself. If then we assume that the curve does possess a gradient, the *asymmetric variations of grid potential* will naturally produce signals in the telephones.

All the above results may be illustrated by the lower curve of Fig. 63, which shows approximately the signal strengths at different points of the curve.

Rectification at Highest Point on Anode Current Curve.—We have hinted just above that the anode current curve begins to fall after the saturation point has been reached.

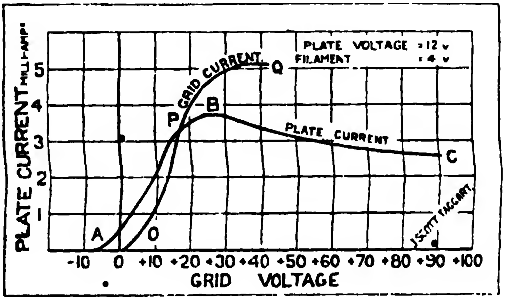


FIG. 65.—Showing how anode current decreases after saturation point.

Usually the curve proceeds gradually upwards, but sooner or later it is bound to come down. This fact has often been overlooked, since it usually requires very high grid potentials to divert a portion of the electron flow to itself, especially when the grid is fairly open and the anode potential high. With 4 volts across the filament of an ES4, French R or VT valve, and 152 volts on the anode, it required +150 volts on the grid before the anode current began to drop. By using small filament currents and low anode voltages we can, however, obtain the highest point on the plate curve with relatively low values of grid potential. Fig. 65 shows how in the case of the same valve, the anode current drops after the grid potential has passed +24 volts. The curve APBC shows the variation of anode current and OPQ the grid current, which, in this case, becomes even greater than the anode current.

It will be seen that if we adjust the grid to +24 volts so that B is our operating point, a variation of grid potential either way will cause a drop in the anode current. Perfect

rectification is thus obtained, but the bend is so blunt at B that the adjustment is only of theoretical interest in the case of most valves. It could only be used for strong signals.*

A somewhat similar result would be obtained if we could develop a vacuum tube, having a curve similar to that of Fig. 66.

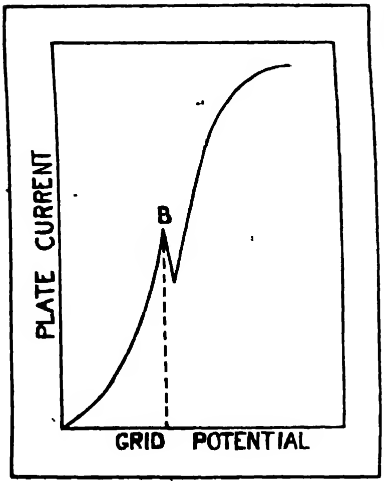


FIG. 66.—Rectification obtained by means of a kink in the anode current curve.

By adjusting the grid potential so as to use B as the operating point, a variation of grid potential either way would cause a drop in anode current. Such a kink has been produced by W. C. White by introducing into a pliotron a small quantity of mercury-silver amalgam.†

Practical Circuits for utilising the Non-Linear Characteristics of a Valve.—Fig. 67 shows a simple circuit suitable for obtaining signals by taking advantage of the non-linear nature of the anode current curve. The coil L is a variable inductance. C is a variable condenser connected in the earth lead when auto-transformer connections are used, as in the present case. P and B_2 constitute a potentiometer arrangement for varying the voltage of the grid. The battery B_2 may conveniently give a voltage of about 20 volts, and the resistance P should have a high value, say 500 ohms. It should be large enough to prevent the battery B_2 from discharging too soon. A switch should be provided for cutting off the current from B_2 when the circuit is not in use. A connection is taken from the halfway point along the resistance to the negative

* Marconi's Wireless Telegraph Co. and F. P. Swann have described in British Patent 105081 (Feb. 25/16) the use of such a point as P on the curve APBC of Fig. 65. Strong signals or atmospherics cause the representative point to travel over the crest B; a decided "limiting" effect is thus produced, strong signals giving no bigger effect than weak ones.

† B. T.-H Co. (General Electric Co., U.S.A.) British Patent 147617 (March 20/14).

side of the filament-heating accumulator B_1. The sliding contact S moves along the whole length of the resistance P. H is an anode battery of about 80 volts * variable in steps. The telephones T are of high resistance and are connected in the anode circuit in such a way that the steady anode current tends to keep the magnets magnetised. The sensitive telephones made by S. G. Brown are marked + and - to facilitate the connection. The left-hand side of these telephones is also connected to the negative end of the filament. They should preferably be connected to the positive side of B_1, in which case four volts less of the battery H would be required for any adjustment. For the sake of uniformity and because we

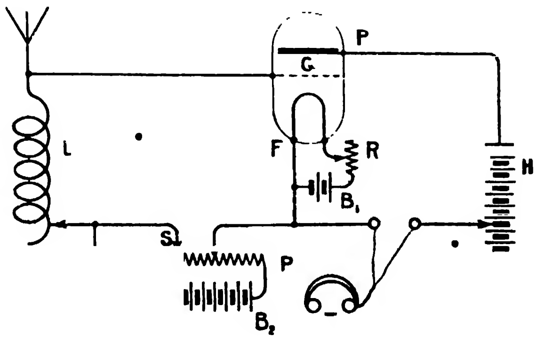


FIG. 67.—A simple receiving circuit in which the non-linear characteristics of the plate current curve are employed.

are considering all potentials as being measured from the negative end of the filament, it is proposed to show both anode and grid circuits connected to the negative side in most cases.

If the resistance P is of the coil type a small condenser of about 0·0003 mfd. may with advantage be connected across S and the middle point of the resistance. This is not so necessary if P is a pencil-resistance.

The method of operation of this set is very simple. The anode voltage may be adjusted to, say, 50 volts and the voltage across the filament to 3·5 volts. During the reception of signals the sliding contact S is moved along the resistance P until the loudest signals are obtained. The filament current

* In the case of RV30, ES2 and V24 type valves, a battery having a maximum voltage of 45 volts is sufficient. Valves of the VT, French, R, or ES4 type require much higher anode potentials.

may be varied by R and different adjustments of H may be made, but a new adjustment of S will be necessary.

There is no need, when using a circuit of this type, to have the grid-potential—anode-current curve completely to the left of the grid zero ordinate This was done previously in order to avoid complications. The curve may be almost in any position.

A simple circuit may be arranged without using a potentiometer. The grid is kept at zero potential, and in order that the grid ordinate may cut the characteristic surface at a suitable point, the curves themselves are moved sideways or upwards by varying the anode voltage or filament current. Fig. 68

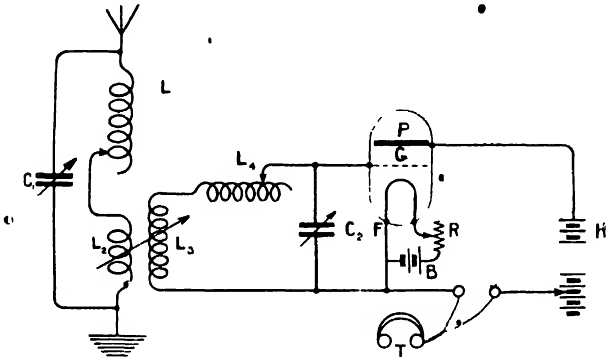


FIG. 68.—Simple long-wave receiving circuit.

shows a circuit which would be suitable. In order to accustom the reader to different variations of the methods of tuning, it is proposed to show various examples as we go along. It will be understood that the methods of tuning are interchangeable. Fig. 68 employs a method suitable for the reception of long waves. The aerial circuit consists of a variable tuning inductance L, a fixed inductance L_2, and a variable condenser C_1. The fixed inductance L_2 is coupled to another fixed inductance L_3 which, in conjunction with the variable loading coil L_4 and the variable condenser C_2, forms part of the secondary circuit. The condenser C_2 should be as small as possible, as is always the practice when using potential-operated detectors.

To obtain the correct operating point, the anode voltage may be varied, in which case the curve may be moved sideways until the grid zero ordinate cuts a bend. By looking at the curves of Fig. 55, we will see that it is not practicable to

use the lower bend. Twelve volts on the anode would give the desired result, but the curve to the right of the ordinate is not as steep as the higher voltage curves and therefore the amplification effect would not be very marked. If we desired to use the lower bend, it would be better to use, say, 54 volts on the anode and give the grid, by means of a potentiometer, a potential of —6 volts. On the other hand, we may very conveniently use the saturation bend. By increasing the anode voltage we would probably get the loudest signals at about 82·5 volts.

It is, however, troublesome to vary the value of the anode battery, and moreover we cannot conveniently vary it smoothly. To do so we would require a potentiometer arrangement in the anode circuit or a variable series resistance of about 10,000 ohms maximum. We can obtain this desired smoothness of variation by using the filament resistance R instead of the anode battery. Fig. 56 showed the effect of keeping the anode voltage constant and increasing the filament current. The curves took the general form of Fig. 69. The curve ABLC is the result of a low value of filament current. By increasing this current the curve changes to ABDKE. We are still working at a point to the right of saturation. By increasing our current filament gradually, we may shift the curve into the position ABDJF so that the ordinate through our normal grid voltage (which is zero) passes through the curve at the initial point of saturation. Signals at this point will be very loud. As we increase the filament current still more, the curve takes up positions similar to ABDNG, signals becoming weaker.

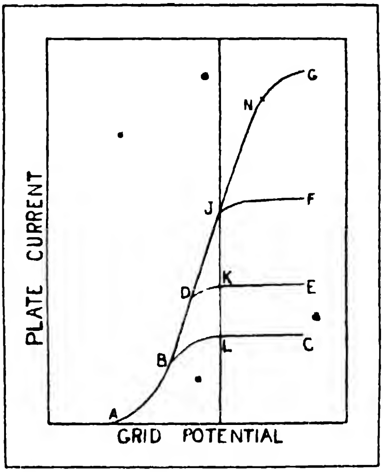


FIG. 69.—To illustrate how the operating point may be adjusted to the initial point of saturation by varying the filament current.

Rectification by Grid Currents.—The author once overheard a student declare that he did not place very much faith in the "rectification at the bends" theory, because he could always

obtain very good signals all the way up the curve and not just at the bends. Even when he adjusted the curve so that the grid zero ordinate cut an *absolutely straight portion of the curve,* signals were heard.

The reader, if a novice, may think the same when he begins to experiment with valves. Doubtless, however, he will soon have conditions similar to those represented by the curve of Fig. 63, which lies completely to the left of the grid zero ordinate. He will notice that rectification is only obtained at the bends or where the curve is concave or convex, and then when he adjusts his potentiometer to the halfway point of the curve, signals completely disappear. He will then probably realise that when his operating point is well to the left of the grid zero ordinate, rectification can only be explained by the asymmetry of the grid-potential — anode-current curve. When the operating point is on the grid zero ordinate or to the right of it, this explanation does not always hold good, since signals are obtained when the characteristic curve is straight. If the reader were to connect a very sensitive galvanometer in the grid circuit of the valve when the operating point lay on the grid zero ordinate (in other words, when the grid was connected to the negative end of the filament), he would find that a small grid current was established when signals were received. He would assume—correctly—that the rectification obtained was due to this grid current.

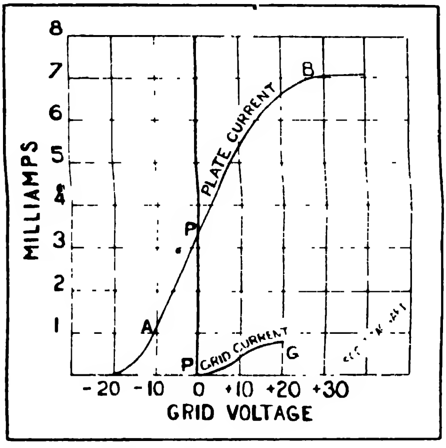


FIG. 70.—Demonstrating rectification produced by a grid current.

Fig. 70 shows a typical grid-potential— anode-current curve APB with a grid-potential—grid-current curve PG beneath it. The grid current is shown on a scale equal to that of the anode current. The operating point we will consider is P on

the grid zero ordinate. These are the conditions existing when a circuit of the Fig. 68 type is used and the anode potential is suitably adjusted. We will suppose that P lies on the steep straight portion of the curve APB.

When wireless waves are being received, the grid of the valve has its potential varied alternately above and below its normal value. If this normal value is negative, the varia-
only are equal. When, however, the grid is at zero potential,
tions negative half-cycles produce their full effect. Positive half-cycles will tend to give the grid a positive charge which will attract negative electrons. These electrons will partially neutralise the positive charge which the half-oscillation is trying to build up on the grid. When the grid becomes negative, the resistance of the space between grid and filament is infinite, but when the grid becomes positive a grid current is established which lessens the resistance of the tube and tends to damp out the positive half-oscillation. A comparable effect is noticed when an external circuit of a battery is completed. The battery may give an E.M.F. of 10 volts on open circuit, but when a resistance is connected across its terminals the E.M.F. may drop to 8 volts. The drop in E.M.F. will depend largely on the amount of current flowing in the external circuit. The less the resistance of the outer circuit, the greater will be the flow of current and the greater the drop in the E.M.F. of the battery.

The natural effect of the grid current is to cause the variation of grid potential about its normal value to be asymmetrical. The negative potential attained by the grid will be greater than the positive potential. Now the anode current curve at P is steep and straight, so that equal variations of grid potential would produce equal variations of anode current. But since the variations of grid potential are not equal, the small positive voltages in the grid will cause only small increases while the large negative voltages will cause large decreases. The resultant effect will be an average decrease in the anode current passing through the 'phones for each oscillation.

In our previous case, the variations of grid potential were symmetrical but the curve was not linear; now the curve is linear but the variations of grid potential are not symmetrical. Fig. 71 shows graphically the process of detection by means of grid currents. The top line shows a group of original

oscillations produced by one complete train of damped waves. These oscillations are rectified on the grid as shown by the second line. That this takes place may easily be proved by connecting a pair of 'phones in the grid circuit, when signals will be heard. The third line shows the amplified oscillations in the anode circuit, and the fourth line the average decrease in anode current for each oscillation. The telephones respond to the complete wave-train and give one click.

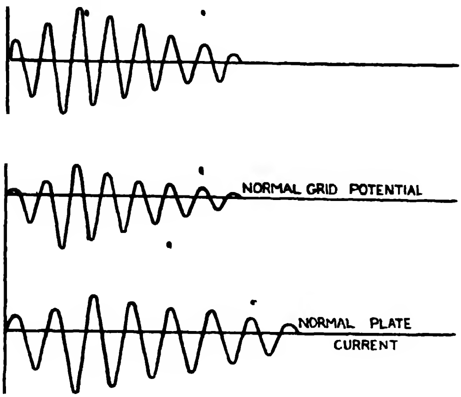


FIG. 71.—Graphical representation of grid current rectification

The strength of signals when using this method of detection will depend largely on—

(a) the slope of the anode current curve ;

(b) the slope of the grid current curve.

The steeper the anode current curve at the point P, the greater will be the amplification effect and the response in the telephones. Moreover, the steeper the grid current curve the greater will be the grid current for a given positive voltage on the grid ; the ultimate positive potential reached by the grid due to the positive half-cycle will consequently be less.

Grid Current Curves.—The grid current curve is of great importance when dealing with the action of the valve as a detector. The amount of current which passes to the grid depends largely on—

(a) the potential of the grid ;

(b) the structural dimensions, etc., of the electrodes in the valve ;

(c) the potential of the anode ;

(d) the value of the filament current.

Naturally, the greater the positive potential of the grid the greater will be the grid current. This was seen in Fig. 70. The grid current curve is usually of the same general shape as the anode current curve. In the case of a hard valve it usually starts very slightly to the left of the grid zero ordinate. The reason why it does not start exactly from the zero point is because even when the grid is at zero volts it cannot help stopping some of the electrons which are on their way to the plate or which have been projected from the filament and would normally return to it. Moreover, electrons are sometimes forced on to the grid even when the latter is at a negative potential. If the grid is of close mesh (in the case of a gauze grid), more electrons will be entrapped and the grid current at zero volts will be greater. The curve APB of Fig. 72 shows the grid currents of the order of 2 microamp. obtained with a French hard valve. It is really a greatly magnified view of the grid current around the point P in Fig. 70. So far we have considered the grid current as commencing at zero grid volts. Although this is approximately correct, we have now reached a stage where a closer investigation can be undertaken.

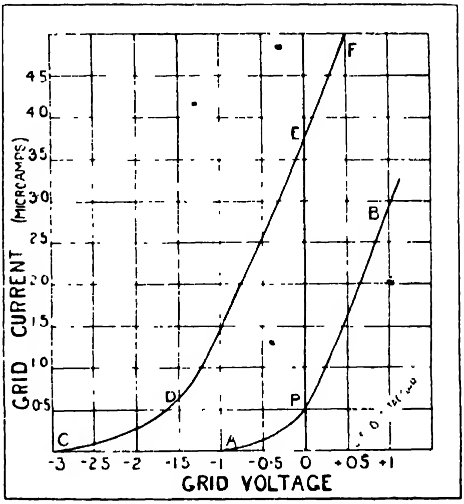


FIG. 72. -Two grid current curves drawn on a large scale.

The grid current curve APB of Fig. 72 is actually very similar to the lower bend of the anode-voltage—anode-current curve of Fig. 29, which we considered when dealing with the rectification obtainable with a two-electrode valve. Let us forget for the moment the existence of the anode and just consider the rectification which may be obtained in the grid circuit. The curve APB of Fig. 72 is concave, and therefore practically any adjustment of grid potential between —1 volt and +1 volt will cause the increase of grid current for a

positive half-cycle to exceed the decrease for a negative half-cycle. The average effect of a complete oscillation is to cause an increase in the normal grid current. Although the curve is concave over a considerable range, there is one point P where there is a pronounced change in curvature, and at this point the rectification effect will be greatest. The bend on the curve APB in this case occurs when the grid voltage is zero. Quite a different grid voltage might, however, easily bring us to the rectifying bend of a grid current curve. The curve CDEF is one on which the bend occurs at −1·5 volts. If we do not desire to use a potentiometer, the whole curve CDEF may be moved to the right until it is cut at D by the grid zero ordinate. The grid current curve is—

(*a*) moved to the right by an increase of anode voltage, and

(*b*) moved to the left by an increase of filament current.

It is therefore a simple matter to move the curve into a position where the best operating point is obtained by zero volts on the grid.

Now that we have shown that there is rectification in the grid circuit we can see that positive half-cycles cause *comparatively* (though actually small) large grid currents which tend to damp out the positive half-oscillations. Looking now at the effect this will have on the anode current, we see that the negative potentials, being the greater, will cause the greater change in the anode current.

Effect of Positive Ions on Grid Current Curve.*—The grid current curves so far given have been those obtained with hard vacuum tubes. If there are molecules of gas inside the bulb, the curves obtained are somewhat different. The electrons as they travel to the anode collide with the gas molecules and disintegrate them; the atoms and their free electrons are separated; the freed electrons join the main stream, and the remaining positive ions are repelled by the anode and attracted towards the filament. We have then, in the gaseous space, both positive ions and negative electrons. The grid being connected to the negative end of the filament is at a lower potential than the remainder of the filament. Consequently, there will be no tendency for the grid to attract electrons. It will, however, attract the positive ions since it is negative with regard to both anode and filament. A flow of positive ions to the grid is equivalent to a grid current flowing in the

* This phase of the subject is admirably discussed by Ralph Bown in the *Physical Review* (see *Electrician*, October 26, 1911, p. 112).

opposite direction to that taken by an electron grid current. In drawing the grid current curve we represent this by showing this portion below the horizontal axis. The portion ACD of the grid current curve ACDE of Fig. 73 represents the flow of positive ions to the grid.

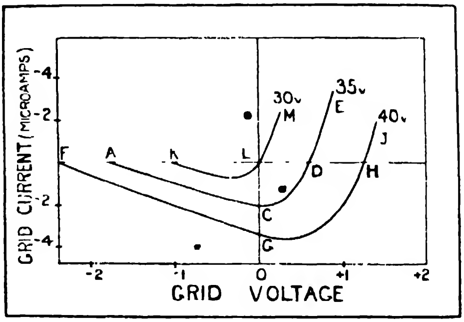


FIG. 73. Grid current curves of soft valves showing presence of positive ions.

It will be seen that the curve rises sharply in the neighbourhood of zero potential. This is because electrons are now beginning to flow to the grid and are commencing to neutralise the flow of positive ions. This flow of electrons commences just before zero volts and increases rapidly as the grid becomes positive. At D the flow of electrons completely neutralises the flow of positive ions to the grid, and the grid current becomes zero. The grid current at any point along the curve ACD is equal to the algebraic sum of the positive ions and negative electrons that strike it. If the negative potential of the grid be increased, the positive ionic current becomes greater and reaches a saturation value at C, after which point the grid current gradually lessens until at A no ions of either sign strike the grid.*

If we increase the anode voltage, the velocity of the electrons will increase and a larger number of gas molecules will be ionised. The supply of ions to the grid will therefore be greater, and we notice an increase in the positive grid current. This is shown by the FGH curve of Fig. 73, which is obtained by using 40 volts on the anode. At the same time, the increased voltage on the anode has a greater tendency to *decrease* the *electron* grid current since it is more capable of drawing up the electrons through the spaces in the grid and preventing them striking the wires. The first effect causes the grid current curve to be lower and the second effect shifts the curve to the right.

* It is interesting to note that a portion of the grid current curve (*e.g.* AC, FG, of Fig. 73) shows a *negative resistance*. This property (explained more fully later) enables continuous oscillations to be produced in a grid oscillatory circuit. See the arrangement of W. C. White (of G.E.C. (U.S.A.) shown in British Patent 148131 (June 3/18).

If we increase the filament current, the number of electrons available is made greater and there is a correspondingly greater tendency for them to strike the grid. The grid current above the line is therefore increased. The grid current below the line, however, is somewhat decreased as shown in Fig. 74. This, Ralph Bown has suggested, is because of the favourable conditions for an increased rate of recombination of positive ions and electrons consequent on the increased number of electrons which come out from the filament, execute a limited low-velocity flight between filament and grid, and then return to the filament. It will be recalled that dissociated gas molecules do not normally recombine, on account of the high velocity of the component electrons and positive ions.

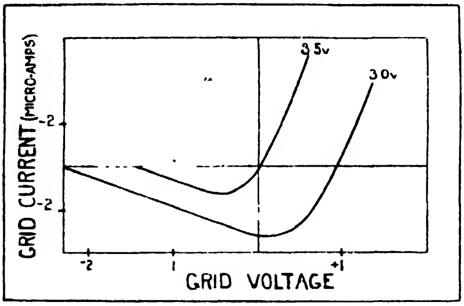


FIG. 74.—Effect of filament current on grid current curve.

The effect, then, of increasing the filament current is to shift the grid current curve to the left and also, when anode voltages are low, to raise it vertically. We thus see that we can easily arrange the best rectifying bend of the grid current curve to occur at zero grid volts, as has been done in the case of the KLM curve of Fig. 73. We can then dispense with a potentiometer.

Fig. 75 shows the lower part of the grid current curve of a hard valve. This valve was able to stand 600 volts on the plate without visible sign of ionisation, and yet it will be seen that there undoubtedly were positive ions in the tube since the grid current curve goes below the line.*

This suggested the use of the grid current curve as an indication of the hardness or otherwise of a vacuum tube. A voltage equal to that normally in use could be placed on the anode and the minimum positive grid current measured by a

* This "reverse" grid current is sometimes called "backlash."

microammeter. This positive grid current would be a measure of the softness of the valve. For example, it was found by the author that, in the case of a certain valve in which the pressure inside was varied, when the positive grid current exceeded 0·25 microamp., the tube was unsuitable for use with high anode voltages as are used in valve transmission. This test is much more reliable than the one in which high negative potentials are given to the anode and the positive anode current, if any, is measured. In the latter test there is no allowance made for ionisation by collision. The positive grid current of Fig. 75 is very small and justifies us in using the term "hard" in reference to the valve.

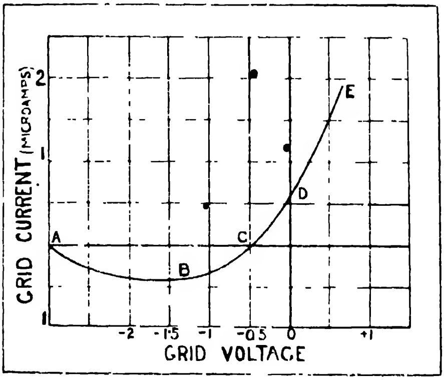


FIG. 75.—Lower portion of grid current curve of a relatively hard vacuum tube.

The structural dimensions of the vacuum tube will largely affect the grid currents. If the grid consists of a cylinder of wire gauze, the amount of grid current taken by the grid will increase as the mesh becomes smaller. The diameter of the wires constituting the grid will also affect the grid current, which will have a greater value when the diameter is large. The closer the grid to the filament, the more current will flow to the grid, since the velocity of the electrons is small and the grid would also collect many of those "wasted" electrons which only make short flights.

The potential of the anode has a very important bearing on the electron current to the grid. We saw this in the few remarks made on soft valves. Fig. 76 shows the effect graphically. Various voltages are put on the anode and the grid current measured for different positive grid potentials. The curves are on such a large scale that the lower portions are not shown very well. It will be seen, however, that a decrease of anode potential makes it very much easier for the grid to draw

electrons to itself. An increase of anode current lessens the current to the grid. The increased force of attraction now exercised by the plate causes the electrons in the neighbourhood of the grid to have a greater tendency to be drawn between the wires out to the anode and a lesser tendency to strike the grid. The curve is moved to the left as we decrease the anode voltage. It will be seen that at 15 volts on the 82·5-volt curve the grid current becomes almost saturated. It will be found that when the grid current becomes saturated the anode current has also reached the same state. The grid has now assisted the anode to draw up all the electrons from the neighbourhood of the filament and at the same time has collected over half a milliampere itself. All the electrons emitted are now either going to the anode or to the grid. A further increase of grid potential will now cause a slight increase of grid current, but at the expense of the anode current, which drops, since electrons are being side-tracked to the grid. As we keep on increasing the grid potential the grid current rises very slowly and the anode current very gradually falls. The sum of the grid and anode currents at any moment past saturation will always be the same and will represent the total electron emission from the filament. These effects are well illustrated by Fig. 77.

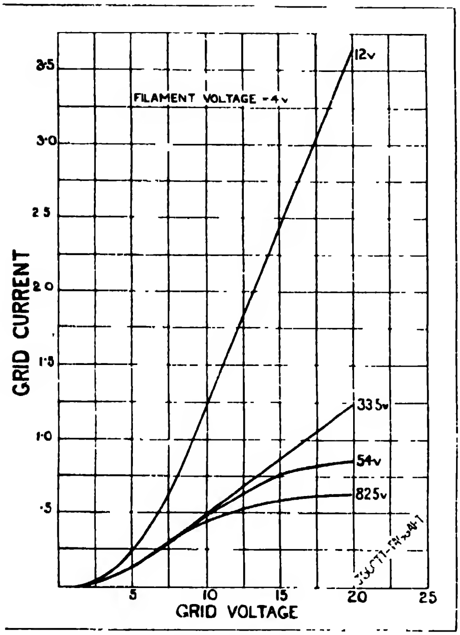


FIG. 76.—Showing effect of anode voltage on grid current.

The effect of increasing the filament current is to provide a large quantity of available electrons. A great many more

will therefore go to the grid for a given positive potential on that electrode. By continually increasing the temperature

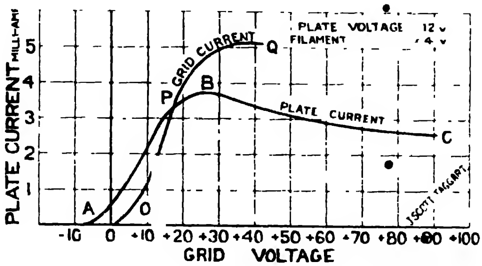


FIG. 77.—Showing how anode current decreases after saturation point.

of the filament the grid current would keep on rising until a space-charge limitation effect sets in. But apart from this, the grid is likely to collect many of the unwanted unemployed electrons which have been emitted from the filament but only normally go for a short flight before returning to their place of origin. Fig. 78 shows a set of grid current curves obtained by increasing the potential across the filament to 4·5 volts. It will be seen that for given grid and anode potentials, the grid current is considerably higher than was the case when the filament current was less (Fig. 76). This point perhaps is more clearly illustrated by the curve

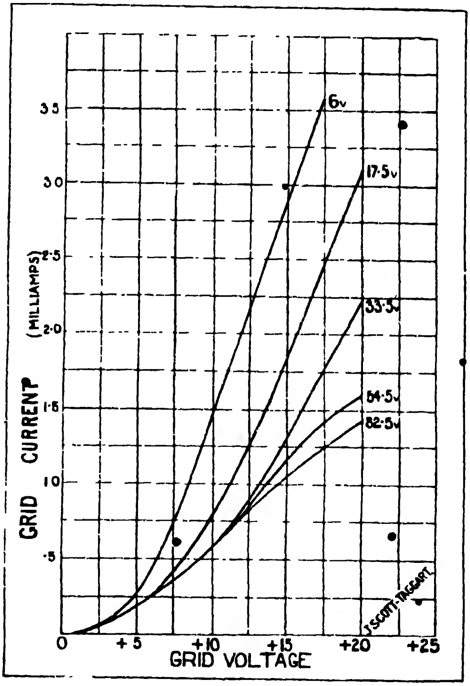


FIG. 78.—Grid current curves to be compared to those of Fig. 76.

of Fig. 79, which shows the variation of grid current in milliamps. with filament voltage, the grid potential being kept constant at +10 volts and the anode at +33·5 volts. The curve rises, showing that the rid current increases with the temperature of the filament.

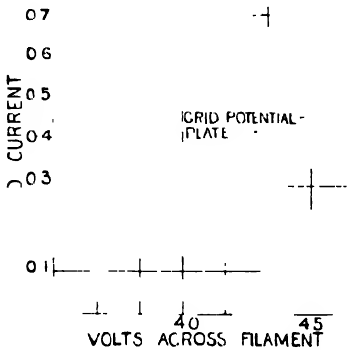


FIG. 79.—Effect of varying filament current on grid current.

Another Rectifying Circuit.—The circuit of Fig 80 has been used with very great success by the author, and its simplicity will appeal to many. As will be seen, the potential of the grid may be varied from zero to +E volts, where E is the voltage of the battery B, by moving the sliding contact along a resistance coil R connected across the filament. The anode circuit includes the telephones T, but there is no anode battery. The anode, however, will be at a potential of +E volts above the negative end of the filament and consequently a small anode current will be established. The battery B is arranged to heat the filament F to a high temperature so that the electron emission is copious. This fact, combined with the very low anode potential, ensures a large grid current when the positive half-cycles of incoming oscillations tend to give the grid a positive potential. The positive half-cycles are therefore effectively damped out if the grid potential be adjusted, by means of the potentiometer, to the rectifying bend on the grid-current curve. The grid-

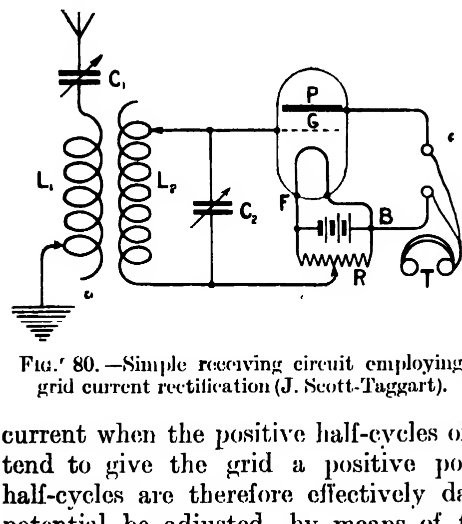


FIG. 80.—Simple receiving circuit employing grid current rectification (J. Scott-Taggart).

potential—anode-current curve is certainly not very steep and so the amplification effect is not as great as it might be, but the rectification effect far more than compensates for this, and very loud signals have been obtained with this arrangement. The higher the temperature of the filament, the louder do the signals become. The grid potential was usually about +4 volts and the voltage of B was normally 6 volts. Very good results have been obtained with the French or R type valve. The results obtained were almost too good to be explained in the ordinary way.*

Combination of Rectifying Effects.—There is no doubt that frequently signals are obtained by a combination of rectifying effects. Suppose, for example, that we are working the valve under the conditions shown in Fig. 81. The circuit used is supposed to be similar to that of Fig. 68. The grid potential is therefore zero volts, and the filament current has been adjusted to the value which brings the initial point of saturation J on to the grid zero ordinate. Now, the very good rectification obtained can be attributed to the asymmetry of the anode current curve at J. There is, however, another factor involved. When the positive half-cycles of incoming oscillations make the representative point travel to the right of J, a grid current is set up. The grid-current curve is shown in the figure. If the grid-current curve starts at 0 (zero volts) or if the bend occurs on the grid zero ordinate, full positive potentials will not be developed on the grid. Consequently, the positive variation of grid potential will be less than the negative variation. For this reason alone, the increases of anode current would be less than the decreases, even if the anode current curve ALJ went straight up to K. But the

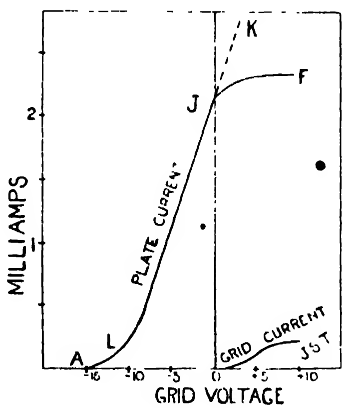


FIG. 81.—Showing combined rectification effects acting in the same direction at the initial saturation point.

* The effect may be due to the action described in the footnote on p. 108.

increases are already less than the decreases since the curve leans over towards F. The two rectification effects therefore combine and act in the same direction.

Another case where both effects are noticeable is illustrated by Fig. 82. The operating point is now at C on a curve ABCJF. It will be noticed that the curve leans over to the right after it has passed C. Now we might at first expect the curve to go straight on as shown by the dotted line. The point C would then be on the steep straight portion. Why should it suddenly lean over? It did not lean over when the curve was situated completely to the left of the grid zero ordinate (Fig. 63). The reason, after a little thought, becomes clear. After we have passed the point C the grid becomes positive and the grid current rapidly rises. Electrons are diverted to the grid and the anode current naturally suffers. The gradient of the CJ portion of the curve is therefore less than that of the BC portion. We can prove that the reason suggested is the correct one by adding together the grid and anode currents for various positive grid potentials and plotting the result—as CDE in Fig. 82. The curve ABCDE is the sort of curve obtained to the left of the grid zero ordinate; there is no bend at C on it. As things are, however, there is a bend at C on our ABCJF curve, and this bend alone would cause an average decrease in anode current for a complete incoming oscillation. Now, since the grid current curve bends in the neighbourhood of O the positive half-oscillations are partially damped out, and we therefore once more get two rectification effects, one due to the asymmetry of the anode current curve and the other due to the asymmetry of the variation of grid potential, acting in unison. The best results are obtained when both effects are most marked; that is, when the anode voltage is low, the filament current high,

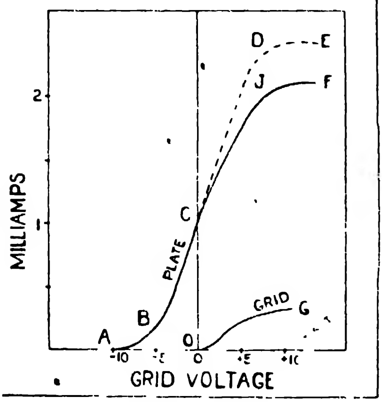


FIG. 82.—Showing how the plate current curve leans over to the right of the grid zero ordinate.

and consequently the value of the grid current great. This no doubt helps to explain the efficiency of the Fig. 80 circuit.

The two rectification effects do not always help each other. Fig. 83 shows us using the valve at C, which is now lower than the halfway point. It is a point where the curve would normally be concave and be of the shape ABCD, D being the beginning of the steep straight portion. The grid current, however, pulls the curve down into the position ABCJ, the curve at C being now practically straight. The rectification

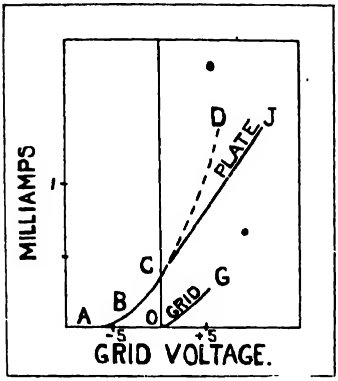


FIG 83.—Rectification effects acting in opposition.

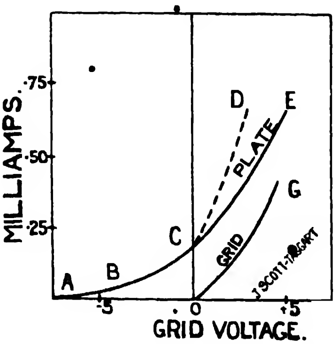


FIG. 84.—Rectification due to grid currents directly opposing rectification due to asymmetry of plate curve.

now obtained is almost solely that due to the damping of the positive half-oscillations.

As we go still lower down on the curve the two rectification effects may act in opposition and completely neutralise each other. Fig. 84 shows a case where this happens. The operating point C is now on the lower bend of the anode current curve, which under ordinary circumstances would be of the shape ABCD. The grid current OG, however, pulls the curve down into the position ABCE. Even so, there is a bend at C, and a complete oscillation would tend to cause a mean *increase* in the plate current. Another effect of the grid current OG is to tend to damp out the positive half-cycle. The positive variation of grid potential will therefore be less than the negative variation. A condition may easily be imagined when the asymmetrical variations of grid potentials cause equal increases and decreases in the value of the anode

current. There will, therefore, be no rectification but a certain amplification.

We can summarise the above facts by saying that the signals obtained on a circuit such as that in Fig. 68 are proportional to the algebraic sum of the rectification obtained by utilising the non-linear characteristics of the anode current curve and that obtained by taking advantage of the effects of grid currents.

Cumulative Rectification by Grid Condenser.—One of the earliest methods of obtaining rectification, and one which holds

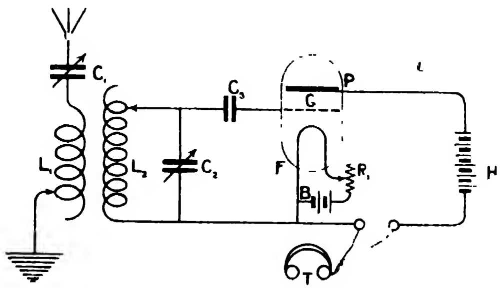


FIG. 85.—Showing use of grid condenser for cumulative rectification

a very prominent place to-day, is that which uses a small condenser in the grid circuit. This arrangement was employed by Lee de Forest, who used it with his "audion" vacuum tube. The explanation of its action has been given by E. H. Armstrong.*

Fig. 85 shows the arrangement as used. The circuit differs from the Fig. 68 circuit in that a condenser C_3 is employed. The action of the condenser C_3 is briefly as follows: When trains of damped waves are being received, the oscillations in the closed circuit L_2C_2 make the grid potential alternately positive and negative with respect to the filament. The condenser C_3 simply acts as a resistance (of the order of about 1000 ohms) towards the high-frequency currents and the grid potential varies in time with the potential across C_2. The condenser C_3 will not, however, allow the passage of direct current, so that clearly there will be no current flowing in the grid circuit. The grid will go on collecting electrons which strike it until it reaches a sufficient potential to repel further electrons. This potential is usually in the neighbour-

* E. H. Armstrong, *Proc. I.R.E.*, September, 1915. See also Langmuir in British Patent 147148 (Oct. 29/13).

hood of zero volts. When, however, the positive half-oscillation affects the grid, the potential of the latter rises above that of a portion of the filament * and electrons immediately commence to flow to the grid. They cannot escape from the grid since the condenser C_3 blocks the way. They therefore charge up the grid and the side of the condenser C_3 connected to the grid. The result is that although the grid potential rises somewhat above zero the normal potential of the grid at the end of the positive half-oscillation is less than it was at the beginning. If E_g were the potential of the grid before signals were received (in our case about zero volts) and E the drop in voltage due to the flow of electrons, the potential of the grid at the end of the positive half-oscillation would be $E_g—E$. The negative half-oscillation now comes along and adds its negative charge to the potential already existing on the grid. If its amplitude is e volts, the grid drops to $E_g—E—e$ volts. The process is repeated and the grid potential rapidly falls. At the end of the train the grid has become considerably negative and the anode current has correspondingly decreased.

Use of Grid Leak.—The grid and the grid side of the condenser C_3 is now charged with electrons. If the vacuum tube is soft, as was the case in the audion originally used, these electrons are neutralised gradually by the positive ions in the tube, and the potential of the grid returns to its normal value E_g in time for the next wave train. It must be remembered that the interval between groups of oscillations is large compared to the actual duration of the group. If the spark frequency of a station transmitting on a wave-length of 600 metres is 1000 the interval between groups of 24 oscillations (0·02 decrement) will be about 20 times greater than the duration of each group. There is consequently plenty of time for the charge on the grid to leak away before the approach of the next set of oscillations.

In the case of hard valves, there are practically no positive ions in the tube, and so the charge on the grid cannot leak away. To remedy this, we use a "grid leak" of two, three or four megohms which is connected across the grid condenser, as shown in Fig. 86. At the end of a wave train the charge on the grid leaks away gradually through the resistance R_2

* This is when we assume that the grid current commences to flow when the grid is at zero voltage.

until the grid resumes its normal potential. The resistance R_2 should be of such a value as to allow the charge on G to leak away completely *just* before the next group of oscillations commences. The anode current will then be kept decreased for quite a considerable time, much longer than the duration of the wave train, and the response in the telephones T will be correspondingly greater. Another reason for the use of a grid leak is that if it were absent, atmospherics or very strong

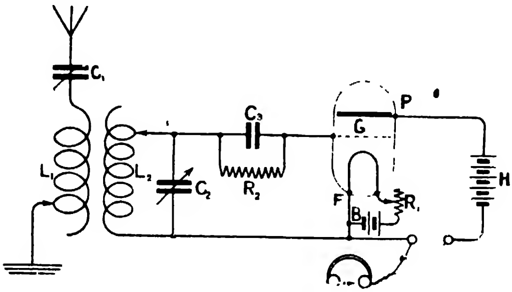


FIG 86.—Showing use of leaky grid condenser for rectification.

signals would paralyse the vacuum tube by giving the grid a very high negative potential.

The most suitable value for R_2 will depend on :

(*a*) The hardness of the tube in use. The harder the valve the greater will R_2 require to be.

(*b*) The damping of the oscillations. The less the damping (the greater the number of oscillations in one group), the lower will have to be the grid leak resistance.

The group frequency. If this is high the resistance R_2 will require to be smaller.

(*d*) The wave-length received. If the waves received are long the duration of a group of oscillations will be greater, and consequently R_2 should be smaller.

(*e*) The capacity of the grid condenser. The resistance of the leak should be higher than the reactance of the condenser, since the oscillations are intended to pass through the condenser. It is impossible to lay down a definite value for the grid leak, but 1 or 2 million ohms (megohms) is usually suitable for a hard valve. The resistance may consist of pencil lines drawn on ebonite, special forms of conducting

glass, platinised glass, liquids, weak solutions of salts in tubes, Indian ink lines on paper, carbonised cellulose,* and other devices.

The value of C_3 should be small in order that small accumulations of electrons may charge it to a high potential. If it is too small, however, it will not pass the high-frequency E.M.F.'s. A suitable value is 0·0003 mfd. In many diagrams the condenser is shown variable, but this appears a somewhat unnecessary elaboration. The reactance of the grid condenser, or its resistance to alternating currents equals $\frac{1}{2\pi fc}$, where $\pi = 3{\cdot}1416$, f = frequency of alternating or oscillating currents, and c the capacity of the condenser in *farads*. The reactance of a grid condenser of 0·0003 mfd. capacity to signals of 1000 metre wave length could be:

$$\frac{1}{2\pi fc} = \frac{1 \times 1{,}000{,}000}{6{\cdot}28 \times 300{,}000 \times 0{\cdot}0003} = \frac{10}{0{\cdot}056} = 1800 \text{ ohms. approx.}$$

This value should be less than the normal resistance of the valve between filament and grid (which is usually 250,000 ohms, but varies greatly). The capacity of the condenser should be much greater than the capacity of the grid. In valves of the French or R types, the grid capacity has been given as approximately 0·000015 mfd.

The resistance R_2 may, if desired, be connected directly across grid and filament as shown by Fig. 87. This connection is sometimes preferable under certain conditions. It will, of course, cause damping of the oscillatory circuit. The arrangement of Fig. 87 is very suitable if we desire to use a condenser and still be able to vary the grid potential. The necessary voltage is given the grid by connecting a potentiometer or battery in

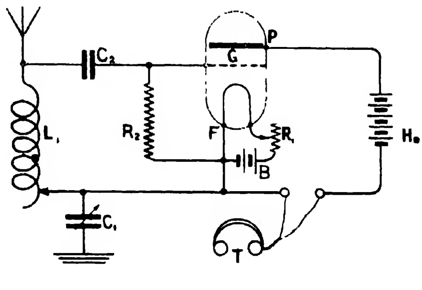


FIG. 87. Another method of using the leak.

* The latter in the form of the half-baked filament of a carbon lamp. This is the most reliable grid leak. See S. R. Mullard's British Patent 131057.

series with R_2. The same effect may also be obtained by connecting an impedance coil in the place of R_2, such as an air or iron-core choke Such a choke may also be used in series with the high resistance to lessen the damping effect. .

The leak effect from the grid will always to a certain extent lessen the sensitiveness of the valve. Not only does the leak allow the electrons to escape *after* the wave-train has passed, but it is allowing them to leak away *all the time*. Of course, we arrange to have the grid leak resistance high enough to make the leaking away gradual, but nevertheless the grid potential can never fall as low as it would have done without the leak. This is more true when the damping of incoming oscillations is small *, and the grid resistance has to be less. This disadvantage of the leak is greatly outweighed by the advantages attending its use, but it is of interest.

Experimental Study of Effect of Grid Condenser.—By using a circuit similar to that of Fig. 88 and connecting a condenser,

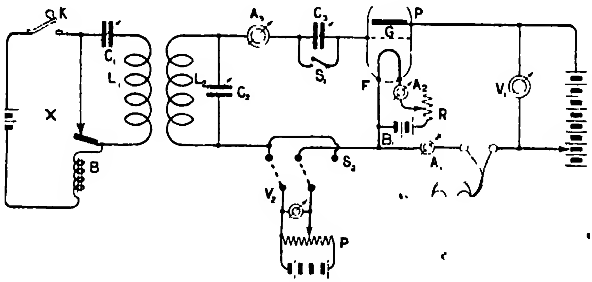


FIG. 88.—Experimental circuit for studying vacuum tube rectification

which may be shorted by a switch in the grid circuit, we can study some of the effects of using a grid condenser. The circuit X is used as the transmitting station, and consists of an inductance L_1 and variable condenser C_1 connected across the make-and-break of a buzzer. This circuit is loosely coupled to the closed receiving circuit L_2C_2 and tuned to it. It is preferable to use an actual transmitting station some distance away, but the artificial transmitter X may be used with success. The microammeter A_3 measures the grid current. C_3 is a variable condenser which may be shorted by S_1. S_2 and P enable the voltage of the grid to be varied when C_3 is shorted. A_1 measures the anode current in milliamperes It is

* As when we use retroactive amplification.

a variable anode battery, and T is the telephone receiver. V_1 and V_2 measure the anode and grid potentials respectively.

By making a series of observations with this circuit, noting the grid, anode, and filament currents for the adjustments which give the loudest signals, all the explanations which have been given so far may be tested.

When the blocking condenser C_3 is in use, no current can flow through it. The grid then will automatically take up the potential at which the grid current is zero. In the case of a soft valve the grid will probably be struck by more positive ions than electrons, and it will, therefore, become positively charged. After a time the grid and the grid side of the condenser C_3 will reach a positive potential sufficient to repel any more positive ions. Although it is not convenient to measure the grid voltage we can note the value of the anode current. We find it, say, to be 0·92 milliamp. We can now find what the potential of the grid was by shorting the grid condenser C_3 and varying the steady potential on the grid by means of the potentiometer until the anode current registers 0·92 milliamp. The voltage of the grid as given by V_2 will obviously equal the potential assumed by the grid when it is isolated by the condenser C_3. If the voltage of V_2 necessary to make the anode current the same as when S_1 is open be +1 volt, the grid potential when the condenser is used will be +1 volt. On account of the positive ionisation, the use of a condenser generally causes the grid to assume a small positive potential. The reverse is the case when the vacuum tube is hard, as is usually the case.

The fact that the grid, when a condenser is used, assumes a potential at which the grid current would be zero if the condenser were absent, may be easily proved experimentally. Draw two curves, one showing the anode current and the other the grid current for different values of grid potential, obtained with a soft valve on the Fig. 88 circuit with grid condenser shorted. Two such curves are given in Fig. 89. It will be noticed that at +1 volt (point *d*) the grid current is zero and the anode current (point D) is 0·92 milliamp. Now open the switch S_1, thereby bringing the grid condenser into operation. It will be found that the plate current will settle down to approximately the value 0·92 milliamp., indicating that the grid potential is +1 volt, the value which gave a zero grid current.

If the valve in use is hard, opening the switch S_1 will

cause a *drop* in anode current as compared to the current when the grid is at zero volts. This is because negative electrons only (or mostly) are being forced on to the grid which collects them until it reaches a potential capable of preventing any more coming to it. This potential may be as much as $-1\cdot5$ volts, and by noting the drop of anode current and dropping a perpendicular line from the representative point to the grid voltage axis, we can say at what potential the current to the grid really commences. In some valves, especially those with fine meshed grids, the insertion of a grid condenser (without leak) will almost or entirely cut off the anode current chiefly on account of the high negative potential attained by the grid.

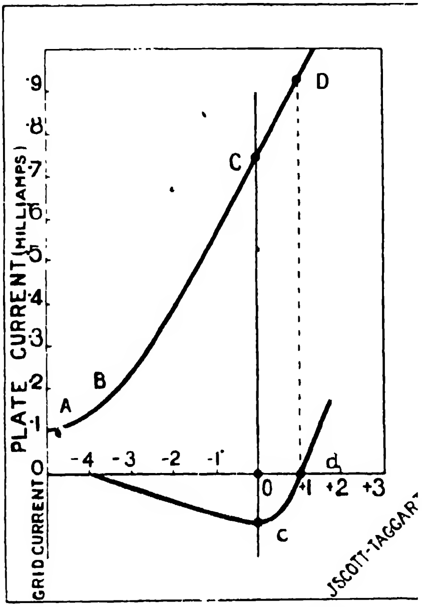


FIG. 89.—To illustrate method of finding potential of grid when a grid condenser is used.

Fig. 90 shows a typical grid-current curve *abcde* obtained with a hard vacuum tube possessing only a few positive ions which cause the portion of the curve *abc* to be below the grid voltage axis. The corresponding anode-current curve ABCDE is shown just above, the points A, B, C, D, E indicating the anode currents corresponding to the grid currents *a*, *b*, *c*, *d*, *e*. When the grid is at zero volts, the representative point is at D on the anode curve and *d* on the grid curve. Electrons are being forced on the grid and produce a grid current (usually of the order of 1 microampere). With an insufficiently delicate grid galvanometer, the grid current might appear to start at 0 (zero volts). When the switch S_1 is opened and the grid condenser brought into action, the anode current immediately drops to C and the grid current becomes zero (at *c*) at about $-0\cdot75$

volts. If the key K of the transmitter X be depressed signals will be heard in the telephones T, and our operating point will be c on the grid current curve and C on the anode current curve. There will clearly be rectification at the point c and during each group of oscillations the grid will collect electrons at each positive half-cycle and the cumulative effect will result in the operating point moving from c along the grid curve towards b. As the grid has become more negative, the anode current has been dropping in unison. The representative point has been moving from C down towards B.

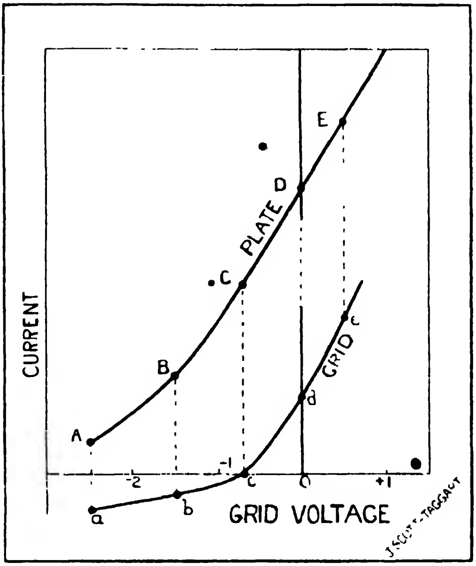


FIG. 90.—Showing normal negative grid potential when grid condenser is used with a hard valve.

The steeper we can make the anode curve between C and B the greater will be the effect of the drop in grid potential, and the louder will be the signals in T.

Effect of Grid Leak on Normal Grid Potential.— It may easily happen that the best rectifying point on the grid current curve is not coincident with the point where the grid current is zero. A case is shown in Fig. 91 which gives curves for a very well evacuated tube; there is no part of the grid curve below the grid potential axis. The normal operating points if a grid condenser were used would be c and C. Now the grid current at c is zero, but the curve is only gradual. At d, however, there is a distinctive bend, which would give much better rectification than the adjustment c. How are we to give the grid a potential of $-0{\cdot}3$ volt to bring us to the point d? A potentiometer cannot be connected across the grid condenser, because the accumulative effect of the latter would be lost. A method which is practical, however, is to connect a high resistance

across the condenser. This will allow some of the electrons on the grid to leak away and the negative potential of the grid will become less; more electrons will, of course, begin to flow again to the grid from the filament, since the repulsion of the grid is now no longer sufficient to keep them away; an equilibrium potential will be established whose value may be regulated to any desired voltage by varying the grid leak resistance. If the resistance is infinitely high, the potential of the grid will drop to a negative value corresponding to *c*. If it be made zero—equivalent to shorting the condenser—the grid potential will be zero, corresponding to the grid current *e*. Intermediate values of the resistance will give intermediate grid potentials. We have here, then, another use for the grid leak.

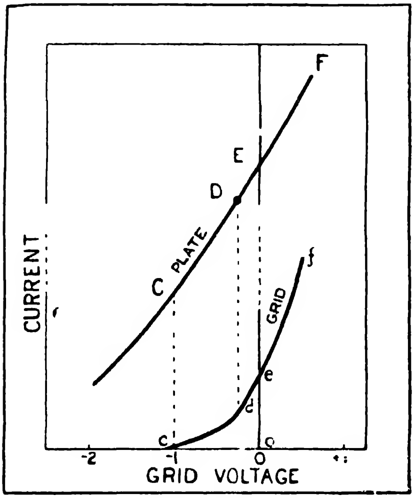


FIG. 91.—Grid and anode current curves of very hard vacuum tube.

The rectifying bend on the grid current curve sometimes corresponds to a positive grid potential. In this case, best results are obtained when the left side of the grid condenser is connected through the oscillatory circuit to the *positive* side of the filament or filament battery. The positive voltage of the battery is communicated through the leak to the grid. This form of connection is sometimes best even when the most suitable grid potential is not positive. It is largely a question of obtaining the most suitable grid potential for the valve in use by balancing the potential on the grid due to the accumulation of electrons and that due to the potential of the connection on the filament battery acting through the leak.*

Miscellaneous Remarks—Since the grid, when it has a condenser in series, assumes the potential at which the grid current

* When signals are being received, the grid potential is no doubt affected to a small extent in a negative direction by the potential drop across the leak, due to the rectified grid current flowing through it.

is zero, a constant value when anode and filament voltage are fixed, the actual size of the grid condenser does not affect the normal potential of the grid. This is shown experimentally on the Fig. 88 circuit by gradually increasing the capacity of the condenser C_3; the anode current remains steady, indicating that the grid potential has not altered. What, however, would be the result if we *suddenly* increased the capacity of the grid condenser? Let us work it out. If the capacity of C_3 is normally 0·00003 mfd., it will take a certain number of electrons on the grid to charge it up to a potential which will cause the grid to refuse any more electrons. It takes time for these electrons to collect on the grid and charge the condenser. It is not an instantaneous process, but may take a second or two. If now we suddenly increase the capacity to 0·0003 mfd. the available electrons on the grid have to charge a condenser of ten times the capacity, and the resultant voltage to which it charges it is consequently much lower than before. The voltage to which a condenser is charged depends on the quantity of electricity and the capacity of the condenser: $V = QC$. In our case, we have increased the capacity C to ten times while keeping the quantity of electrons Q the same. The voltage V to which the condenser is charged therefore drops to one-tenth its former value. The potential of the grid will therefore drop to one-tenth of its former value. If this is -1 volt the result of increasing the grid capacity suddenly will be to make the potential of the grid $-0·1$ volt. The anode current will naturally suddenly increase. But this increase will only be momentary. When the potential of the grid is only $-0·1$ volt electrons will commence to flow once more to the grid, and will continue to flow until they have charged the grid condenser of 0·0003 mfd. capacity to the grid potential (-1 volt) at which the electron flow ceases. The grid potential therefore drops again to -1 volt and the anode current falls to its normal value. Increasing the capacity of the grid condenser by turning the handle of the latter suddenly will, therefore, cause a momentary increase of anode current, and the milliammeter in the anode circuit will give a kick forward. If the condenser is only turned slowly, the electrons have time to rush in and compensate by their additional charge the increase in capacity, and no variation of anode current is noticed. This phenomenon explains why, when first switching on the filament current of a grid condenser rectifying valve, some seconds frequently

elapse before signals develop to their full strength. The grid condenser is being charged up by the flow of the electrons to the grid, and it takes a small interval of time before the potential reaches its critical value. This interval is longer, the greater the capacity of the grid condenser.

Fig. 92 is a circuit which will show a fact frequently not quite understood by students. The arrangement is self-explanatory.* If the key K be kept steadily depressed, the large negative voltage of the battery B does not cause any drop in the anode current on account of the presence of the grid condenser. If the battery B be reversed the anode current still remains at the same value as if the battery B was out of the circuit. Now release the key K and note the anode current. It does not vary if the insulation of C is infinite.

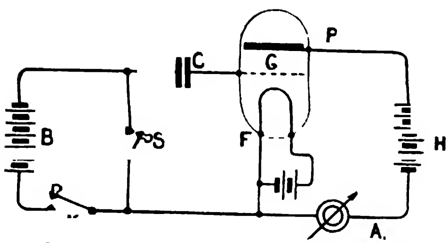


FIG. 92.—Circuit for studying effect of grid condenser.

If now we close the key *suddenly*, a pulse of potential will be transmitted through the condenser C. If the negative side of B is connected to C, the result of this pulse will be to produce a momentary negative charge on the grid, which will cause a drop in anode current. It must be clearly understood that the battery B does not supply electrons to the grid. All it does is to cause the free electrons in the grid and the plates of C connected to the grid to heap up on the grid, while the positive ions are left behind. The result is a momentary excess of negative electricity on the grid. When, however, the effect of the sudden pulse is over, the heaped-up electrons distribute themselves evenly and neutralise the positive ions, and the grid potential returns to zero. The total number of electrons on the grid and condenser plates remains identical; it is only their distribution that is affected by the negative pulse of E.M.F. The negative half-cycles of incoming wireless waves have a very similar pulse effect. They do not contribute actual electrons to the grid, but merely cause it to become more negative by heaping up already existing electrons on to the electrode.

* In this experiment the key S may be left open throughout.

If the positive side of B is connected to C, the reverse effect is produced. Positive ions are left on the grid, the electrons being heaped up on the inner sides of the condenser plates connected to the grid. The momentary pulse of positive potential on the grid causes a sudden temporary increase in anode current. When the effect of the pulse is over the electrons and ions neutralise each other once more, but is the grid potential the same as before? No, because the positive ions when they were left on the grid attracted electrons which collected there. When the effect of the pulse is over, these electrons remain and give the grid a potential lower than its normal value. We see this experimentally, by noticing that the anode current registered by the milliammeter A_1 is lower than it was before we gave the grid a positive pulse. Here then we see actually with our eyes on a large scale what goes on—on a very small scale and at the rate perhaps of 500,000 times per second—when oscillations cause the grid potential gradually to drop.

Demonstration of Grid Condenser Rectifying Action.—Developing his method of demonstrating the cumulative rectifying action given above, the author devised a more elaborate arrangement which is shown in Fig. 93. B is a

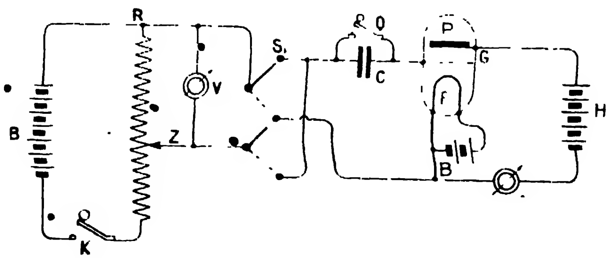


FIG. 93. Circuit for demonstrating cumulative rectification.

battery of, say, 20 volts; R is a potentiometer resistance along which slides a contact Z. The potentials obtained are measured by a voltmeter V and may be applied in either direction by means of the commutator S across the left side of C and the filament. The grid condenser C may be shorted, when desired by means of Q. The most important part of the circuit is the key K. It may be an ordinary key, but as the speed of the "make" affects the pulse and as the speed will vary every time on an ordinary key, the kind shown in Fig. 94 is

K

recommended. ABC is a flat, springy strip of metal having a silver contact B which normally rests on another contact D.

An arm EFG is pivoted at F in a vertical support, the end E normally being under the spring at C. On pressing the end G down, the end C of the spring is raised, the contact B leaves D, until on further depressing G the end E of the arm slips off the spring at C and the action of the latter brings the contacts B and D together sharply. Any other arrangement which brings the contacts together always at the same rate may be used.

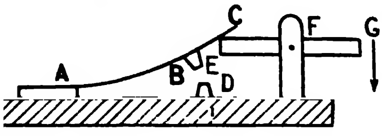


FIG. 94. Special key for use with Fig. 93 circuit.

If the key K be depressed and the circuit BRK thus closed, a potential difference will suddenly arise between the end of the resistance R and the sliding contact Z; this impulse of E.M.F. will be communicated through the condenser C to the grid. Its relative value may be found by closing K and measuring the steady potential difference across the voltmeter V. It may be regulated by moving the sliding contact Z to the required position on R. The impulse on the grid may be made positive or negative by using the commutator switch S_1. When K is open, the grid is connected through the condenser, *via* the voltmeter and resistance RZ to the negative end of the filament. We can, therefore, note the normal anode current. When K is open and the grid condenser shorting switch Q is closed, the grid is at zero volts. First calibrate the resistance R by depressing K steadily and noting the voltage given by V when Z is moved along the resistance. Whenever we are about to experiment with the circuit let us close the switch Q for a moment and then open it; this will ensure that the grid is at its correct normally potential and has no additional electrons.

Let us now proceed with a demonstration of the detector action of the grid condenser.

Open switch K and then Q. Adjust Z to 5 volts and the commutator S to the position shown on the figure. Note the normal anode current given by the milliammeter A; let its value be represented by I_0. Close K suddenly. A pulse of +5 volts will be communicated through C to the grid. It will cause a momentary increase in the value of the anode current.

When the effect of the pulse is over, however, the anode current settles down to a normal value *less* than its previous normal value I_0.

Let this new value be $I_0 - i_1$ where i_1 is the decrease. The fact that the anode current has decreased indicates that the potential of the grid has fallen, a fact easily explained by assuming that the grid has, during the time it was positive, attracted and entrapped negative electrons. If the original potential of the grid be called E_g (a negative value of about half a volt usually in the case of a hard valve), and the fall in potential due to the collection of electrons be represented by e_1, the normal potential of the grid after the positive pulse will be $E_g - e_1$.

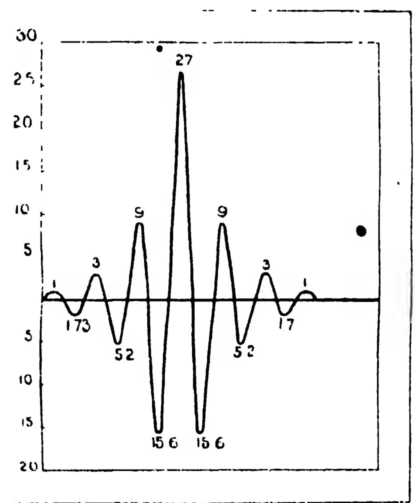


FIG. 95.—A train of damped oscillations.

We now propose to give the grid pulses of a value and sign to correspond to the oscillations produced by one complete train of damped waves. Each subsequent half-cycle we will consider greater by a certain amount than the preceding one until after the maximum amplitude is reached, when their amplitudes will begin to *decrease* by fixed amounts. This is not exactly true, but it will be an approximation to the real state of affairs.*

We have already given the grid the first positive half-oscillation and will now proceed to give it a negative pulse. Open K, adjust Z to 10 volts and the commutator S to the position shown by the dotted lines. Close K suddenly. A momentary negative potential will be placed on the grid. The anode current will fall from $I_0 - i_1$ to a lower value, but after the pulse is over, will return again to the value $I_0 - i_1$. The grid has not acquired

* If A_1, A_2, A_3 are the amplitudes of successive positive half-cycles, conditions are actually such that $\frac{A_1}{A_2} = \frac{A_2}{A_3}$, as shown, for example, in Fig. 95.

anything but a merely temporary charge due to the negative pulse. The grid potential will fall from $E_g - e_1$ to $E_g - e_1 - 10$ volts, but will return again to the potential $E_g - e_1$ after the pulse is over.

Now give the grid a pulse of $+15$ volts. The grid will tend to take up a potential of $E_g - e_1 + 15$. This potential will probably be positive and will not reach its full value on account of the electrons which will flow to the grid. At the end of the pulse the grid potential will be less than $E_g - e_1$. Let it be represented by $E_g - e_1 - e_2$. The normal anode current at the same time has dropped to a value lower than $I_0 - i_1$, which we can call $I_0 - i_1 - i_2$.

The process may be continued until the normal grid potential has fallen to such a value that the positive half-cycle no longer tends to make the grid positive. There is therefore no tendency for the grid to collect more electrons and its normal negative potential remains steady until the end of the wave-train.

Graphical Representation of Grid Condenser Rectification.—The top line of Fig. 96 shows a somewhat typical group

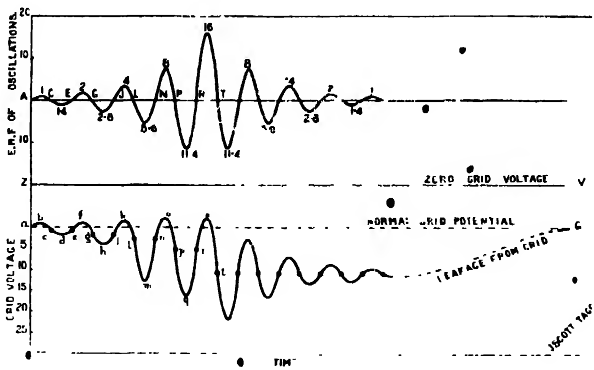


FIG. 96.—Detailed graphical representation of cumulative rectification.

of damped oscillations. The voltage amplitudes of each half-cycle are given on the figure and are made large to make the process of rectification clearer. The second line shows the effect of these oscillations on the potential of the grid. The line ZV represents zero volts on the grid. The line aG is the normal grid potential which in the case of a hard valve is a

negative value and in the case of a soft valve is frequently positive. If ever the grid attains a potential higher than *a*G, it will collect electrons.

The first positive half-cycle will tend to cause a slight increase in the potential of the grid as indicated by *b*. At the end of the positive half-cycle the grid will have attracted and entrapped a number of electrons which will cause it to assume a potential below *a*G. Let us suppose that this fall of potential is 0·5 volts. The grid potential is now at *c*. A negative half-cycle of 1·4 volts now comes along and causes the grid potential to drop to *d* (–0·5 –1·4 volts = –1·9 volts). At E, the end of the negative half-cycle, the grid potential will be –0·5 volt as shown at *e* on the grid potential line. The negative half-cycle has only caused a temporary change in the potential of the grid. The second positive half-cycle of +2 volts amplitude now affects the grid, whose potential it tries to raise to (–0·5+2) volts. It raises it above the *a*G line, but the resulting flow of electrons prevents the grid potential rising to +1·5 volts. At the end G of the second positive half-cycle the grid potential will drop still further than at the end of the first half-cycle. Since the second positive half cycle tries to raise the grid potential 1·5 times as high as the first, we may roughly assume that the grid potential will be lowered by 1·5 times the amount. We can say then that at G the grid is at (–0·5–0·75= –1·25) volts (*g*). The negative half-cycle following causes the grid potential to drop to (–1·25—2·8)= –4·05 volts (*h*). At the beginning of third positive half-cycle (*j*) the grid is back again at —1·25 volts. This half-cycle (4 volts) causes it to rise to a value a little above *a*G, but at the end of the oscillation the grid assumes a potential of –1·25 –(4 – 1·25)(0·5)= –2·62 volts. The third negative half-cycle varies the grid potential from —2·62 volts to –2·62—5·6= –8·22 volts (*m*) and back again to –2·62 volts (*n*). At the end of the fourth positive half-cycle the grid will be at a potential of –2·62 –(8 – 2·62)(0·5) = —5·31 volts (*p*). The fourth negative half-cycle will cause the grid potential to drop to –5·31 –11·4= –16·71 volts (*q*) and then to return again to the normal value —5·31 volts (*r*). The fifth and largest positive half-cycle will attract a large number of electrons and at the completion of the half-cycle the grid potential will drop to —5·31 –(61—5·31)(0·5)=—10·65 volts (*t*). The following

negative half-cycle causes the grid potential to drop from —10·65 volts to —10·65—11·4=—22·05 volts and to return again to —10·65. The sixth positive half-cycle is smaller than the previous one and raises the grid potential from —10·65 to —10·65+8=—2·65 volts. The grid potential does not this time rise above the line aG, and consequently, no electrons being drawn to the grid, the potential of the latter returns to —10·65 volts. The sixth negative half-cycle causes the grid potential to drop to —10·65—5·6=—16·25 volts, and return to —10·65 volts. The seventh positive half-cycle raises the grid potential from —10·65 volts to —10·65+4=—7·65 volts and then returns it to —10·65. It is needless to go further. Once the point has been passed where the oscillations no longer tend to raise the grid potential above the value at which an electron current begins to flow, the grid remains at a steady normal potential which ceases to drop. Its potential is varied above and below this normal potential by the remaining oscillations but the operating potential itself does not fall. The last few oscillations do not really help the process. In our special case the steady grid potential falls to —10·65 volts and remains there once the fifth positive oscillation has passed. This need not always be the case. If we had assumed that the electrons flowing to the grid caused the potential of the latter to drop only a slight amount, the steady grid potential might have dropped to only —6 volts at the end of the fifth positive half-cycle, in which case the sixth positive half-cycle of +8 volts amplitude would become effective and help on the process.

We can restate the above facts more accurately. Let us look again at Fig. 90. The normally operating point is c on the grid current curve *abcde*. As the rectification at c proceeds the potential of the grid falls and the operating point slides back towards b. A time will come when the positive half oscillations are not large enough to move the representative point further than c, and perhaps not even as far. The curve at b is straight and therefore the rectifying action ceases and the normal potential of the grid remains steady at a decidedly negative value.

If the grid condenser were perfectly insulated, the grid potential, as given by Fig. 96, would remain at —10·65 volts indefinitely.* As, however, we desire to adjust the valve to

* Providing there was no leakage in the valve.

the best operating point before the next train of oscillations comes along, we use a high-resistance leak across the grid condenser which allows the surplus electrons to leak back to the filament and restores the grid potential to its normal value aG. A dotted line from the end of the oscillations to G shows the potential of the grid gradually returning to its normal value, which should be reached just before the next group of oscillations arrives.

The above graphical example must not be considered exact. It will, however, serve as a rough and ready explanation of the phenomenon. The voltages considered are, of course, very much higher than those found in actual practice, and have only been chosen for the purpose of the explanation.

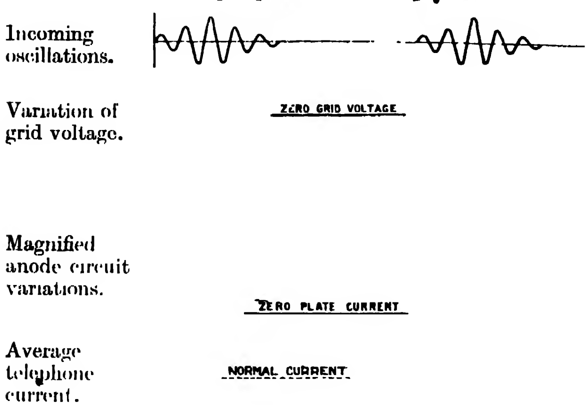


FIG. 97.—Graphical representation of cumulative rectification.

Audio- and Radio- Frequency Components of the Anode Current.—So far we have only considered graphically the variation of grid potential during a wave-train. The effect of this fluctuating grid potential on the normal anode current is shown in Fig. 97. The top line shows two successive groups of oscillations. The second line shows the effect of these oscillations on the potential of the grid; the effect of the grid leak is also shown. The third line shows the amplified anode current variations produced by the varying potentials on the grid. It is assumed that the straight steep portion of the current anode curve is in use.

It will be seen that the anode current is varied in two ways. There is a steady drop followed by a return to its

normal value. These decreases occur at each wave train. Their effect is to cause a click each time in the telephone receivers if the latter are included in the anode circuit. The anode current is, therefore, varied at a low "audio" frequency, a frequency which can be heard in the telephones. The effect of audio-frequency changes in anode current on the 'phones is shown in the fourth line of Fig. 97.

The anode current is also varied at a "radio" or high frequency. While its normal value is steadily falling there are high-frequency variations on either side of this value. The third line shows clearly the high-frequency variations which are superimposed on the low-frequency decreases. The telephones are unaffected by the radio-frequency changes of anode current which are in time with the incoming oscillations; they only respond to the audio-frequency variations. The existence of the *radio-frequency component* is very important, and great use is made of it, as will be seen later. So far it has been wasted. Its actual form is not quite the same as the original oscillations, but it has the same frequency. Owing to the rectification effect the negative half-cycles are more developed than the positive ones. The tail-end oscillations in Fig. 96, however, will be perfectly reproduced since they are not rectified.*

Combined Rectification Effects.—Since the effectiveness of the grid condenser rectifying arrangement depends upon the action of grid currents, it is usual to use rather a lower anode voltage to enable the grid to attract electrons more easily when its potential is raised above its normal value. For a similar reason, it is usual to use a rather large filament current. The effect of these adjustments is usually to cause the grid current curve to rise steeply to the right of its rectifying bend.

We have seen that the operating point slips backwards to the left of the bend on the grid current curve during the reception of a group of oscillations. At the same time the representative point on the anode current curve also moves down. In order to get the maximum response in the telephone receivers, the portion of the anode current curve traversed by the representative point should be straight and as steep as possible. The lower bend must be avoided, but for another

* The separate audio and radio frequency variations of the anode current might almost be compared to the downward swoop of an aeroplane and the simultaneous rotation of its propeller.

reason. Not only will the representative point move along a curve of smaller gradient as the grid becomes negative, but it will move up the steep part of the anode current curve when the grid potential is raised above its normal value, as it is to a certain extent during the first part of each group of oscillations. This additional rectifying effect will lessen that obtained by the cumulative action of the grid condenser.

The opposite result is obtained at the initial point of saturation. Here, we get a good fall of anode current as the grid potential drops, and, moreover, when there *is* a tendency for the grid to rise above its normal value, the resultant rise in anode current is very small, since the anode current curve is leaning over to the right. This adjustment, then, is very good provided the values of filament current and anode potential are not prejudicial to good cumulative rectification. Unfortunately they usually are, and it will be best, as a general rule, to use the valve at a point on the straight portion of its anode current curve.

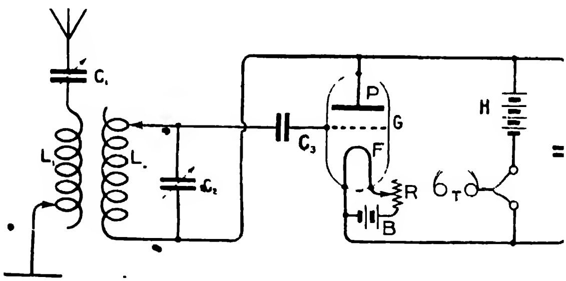


FIG. 98.—A Lee de Forest type of circuit.

Another "Audion" Circuit.—Fig. 98 * shows a special method of connecting up a vacuum tube for rectification purposes. It was developed for use with the audion by Lee de Forest and the connections are frequently used in the United States. The essential feature of the circuit, apart from the grid condenser, is the fact that the leads from the receiving oscillatory circuit are connected to the grid and plate of the vacuum tube and not to the grid and filament as has been previously shown. A condenser C_4, of about 0·0004 mfd. is connected across plate and filament.

There is nothing very complicated about the theory of the

* Lee de Forest, British Patent 3950/15 (March 12/14).

circuit. The condenser C_4 acts as a good conductor of high frequency currents, so that there is practically no *high-frequency* change of potential between the plate and the filament. When signals are being received, an oscillating E.M.F. is established between plate and grid, but as the potential difference between plate and filament hardly varies, the grid potential oscillates with respect to the filament. The action is, therefore, similar to that of circuits using the more ordinary connections.

It will be noticed that in Fig. 98 the upper end of the closed circuit inductance L_2 is connected to the grid. This end is the one furthest from the earth side of L_1. It is what is known as the "high potential end" of L_2. The potentials at this end are the higher and the leads to it should be very carefully insulated. The high-potential end of the inductance should invariably be connected to the grid. The other end is the low potential end and is connected to the low potential part of the vacuum tube, namely, the filament which is frequently earthed. In the present circuit the lower end is connected to the plate and so, *viâ* C_4, to the filament. De Forest's circuit is usually modified when hard vacuum tubes are used by connecting a leak across G and F.

Further Remarks on Rectification.—We have indicated that a grid leak connected directly across the grid and filament may serve as a convenient means of giving the grid a suitable normal operating potential. Fig. 99 shows a receiving circuit in which advantage may be taken of this fact.

A grid condenser C_3 is connected as shown. A resistance R_1 of several megohms is connected through a potentiometer P to the filament. The potential of the grid may be made positive or negative as desired by moving the slider S below or above the middle tapping on the potentiometer resistance. We are thus able to adjust our valve to the best operating point on either the grid or anode current curve. For example, we could work the tube at the initial point of saturation by suitably adjusting the grid potential by means of P. When P tends to make the grid negative, the grid current will be zero and consequently there will be no potential drop in R_1 in spite of its high resistance. If the point S had a potential of -2 volts with respect to the middle point of P, the grid would likewise have a potential of -2 volts with respect to the filament. If, however, the potential of S were $+2$ volts with respect to the middle point of P, the grid would be

positive with respect to the filament and a grid current would flow through R_1. There would consequently be a small potential drop across R_1 and the potential of the grid would be rather less than + 2 volts.

A circuit such as that of Fig. 99 is suitable when it is desired to use cumulative rectification and yet be able to vary the normal grid potential. Frequently, the bend on the grid current curve occurs when the grid potential is slightly positive, in which case the Fig. 99 circuit might be used.

Modified forms of the circuit are frequently found. Sometimes, the potentiometer is omitted and the foot of R_1 connected to the negative side of the accumulator B and sometimes to the positive side. Another arrangement consists in connecting

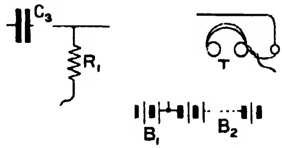


FIG. 99. Showing a means of varying the normal grid potential.

the foot of R_1 to a sliding contact on a potentiometer resistance joined across the accumulator B. This would allow the potential of the grid to be varied from zero volts to a positive value equal to the voltage of the accumulator. Several grid cells could be connected between the foot of R_1 and a sliding contact on a resistance across the filament battery. A variation of 4 or 6 volts could thus be obtained in the grid potential.

The value of the arrangement shown in Fig. 99 lies chiefly in its application to multi-stage amplifiers * which will be discussed in a later chapter.

* *See*, for example, British Patents 127013 and 127014 of Brillouin and Beauvais

CHAPTER IV.

THE VACUUM TUBE AS AN AMPLIFIER.*

Low-Frequency Amplification.—We have already seen how the vacuum tube may act as an amplifier. The best conditions for amplification are briefly as follows :—

Amplification of speech and alternating or oscillating current variations which are to be reproduced faithfully :

(*a*) The portion of the anode current curve used should be steep and straight.

(*b*) It should lie to the left of the grid zero ordinate to avoid grid currents.

(*c*) The normal grid potential should consequently be negative.

(*d*) The representative point should never move off the steep straight portion, which should be long enough to deal with the amplitude of the incoming alternations.

Amplification of unidirectional pulses †:

(*a*) The portion of the anode current curve used should be steep and straight, although absolute straightness is not essential.

(*b*) It need not lie to the left of the grid zero ordinate.

(*c*) The normal grid potential may be any value but may conveniently be zero volts.

(*d*) It should be so adjusted that the representative point does not leave the straight steep portion of the anode current curve.

(*e*) The valve should preferably be so connected that the grid receives a negative pulse of potential, unless the operating point is well to the left of the grid zero ordinate. If the grid receives a positive pulse, grid currents may be established which will lessen the effectiveness of the positive charge.

It will thus be seen that the amplification of currents of an

* See also J. Scott-Taggart, "Valve as an Amplifier," *Wireless World*, Jan., Feb., March, 1918.

† It must be remembered that unidirectional pulses fed into a transformer produce alternating current.

alternating nature requires special precautions which are not necessary when dealing with unidirectional pulses. As we have studied in greater detail the effect of grid currents, we are now more competent to arrange matters so that the rectification effects which we aimed at in the last chapter are eliminated.

Fig. 100 shows an amplifying circuit. The coil T_1 is the primary of a step-up transformer, the secondary T_2 of which is connected across the filament F and grid G of a three-electrode vacuum tube. In the anode circuit is an anode battery H and a transformer winding T_3. A secondary winding T_4 enables us to draw away any power generated in the primary T_3.

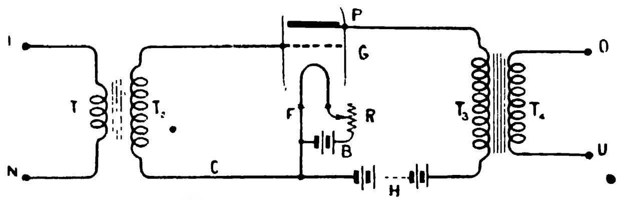


FIG. 100.—Simple amplifying circuit.

The transformer T_1T_2 is of the step-up type in order to magnify the E.M.F.'s across T_1 and so obtain as great a variation of grid potential as possible. The transformer winding T_3 should have a high resistance approaching that of the space between filament and anode. The winding T_4 has fewer turns than T_3 if we desire to obtain strong currents at low voltage, but many more turns if we desire high E.M.F.'s across OU.

The circuit IT_1N may be termed the *input* circuit and OT_4U the *output* circuit of the amplifier. A weak alternating current applied to the input terminals I, N, will cause high potentials to be set up across the secondary T_2 and consequently across the grid G and filament F of the valve. This will cause large variations of anode current through the transformer winding T_3. When the anode current is flowing steadily through T_3, no currents are set up in T_4. When the anode current is varied, however, an amplified alternating current is set up in T_4 which will actuate any suitable instrument, such as a telephone receiver, connected to the output terminals O, U.

This typical circuit is found in very many devices used in wireless telegraphy and telephony. It may be used even as

a generator of high-power current, in which case the valve used is of large size; the battery II is replaced by a dynamo and the filament is heated by current from a dynamo or alternator.

Since the circuit is of such importance, it will be worth while to consider its operating characteristics. What are the disadvantages of the circuit as it stands in Fig. 100? There are several, and they will be readily seen by referring to the typical grid current curve of Fig. 101. Since the grid is connected through the winding T_2 to the negative end of the grid, our operating point is *d* on the grid current curve *abcde*. This is the point which corresponds to zero volts on the grid. The grid current here is comparatively considerable and equal increases and decreases would not be produced by an alternation. The slope of the curve increases rapidly and the increase of grid current due to + 1 volt, for example, will be greater than the decrease produced by —1 volt. There will, therefore, be a tendency to prevent any positive half-alternations on the grid reaching the same amplitude attained by negative half-cycles.

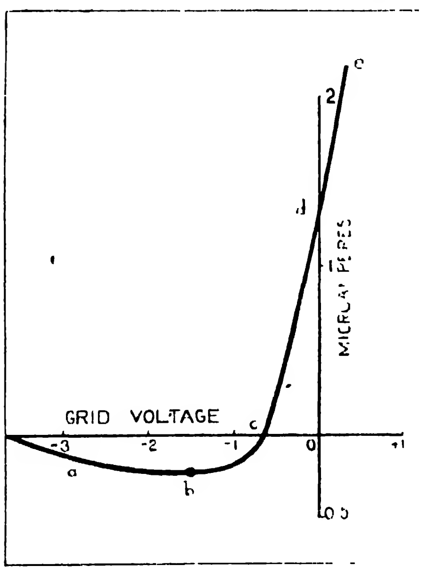


FIG. 101.—Showing best operating point on grid current curve for amplification.

The transformer $T_1 T_2$ will be at a disadvantage in two ways. The load on the secondary T_2 will be appreciable since the grid current at *d* is fairly large, and consequently it cannot "step up" to as high a voltage as if there were no grid current. Also, the load will be variable since the grid current is not symmetrical about *d*.

Owing to the grid current, energy is used up in the secondary

of the transformer. Moreover, since the variations of grid potential about the normal value are not equal, the variations of anode current will not be symmetrical, a certain amount of distortion being thus produced.

These disadvantages may be largely overcome by using an appropriate negative voltage on the grid. A potential of -0.75 volt would bring us to the point c, a point suitable for rectification and consequently fatal to accurate amplification. A potential of -1.5 volts, however, brings us to a very suitable point b on the grid current curve. Here the grid current is very small and consists of positive ions. The load on the transformer secondary T_2 is very small and the grid circuit absorbs practically no energy. The grid consequently rises to greater positive and negative potentials. These potentials will, moreover, be equal on either side of -1.5 volts since the grid current remains constant for a considerable distance on either side of the operating point b.

From the above, we see that it is advisable to have a negative voltage of about -1.5 volts on the grid. We can obtain this by suitably connecting a small dry cell somewhere in the grid circuit, say at C (Fig. 100). This will be quite suitable when the E.M.F.'s to be amplified are small. If they exceeded 1 volt, the representative point would pass the point c during the effect of a positive half-cycle. Rectification would result, and distortion in the anode circuit would follow. We might, therefore, find it advisable to give the grid a more negative potential, say -3 volts. The grid current curve at the new point a is practically the same as it was at b. The slope from b to a and onwards is actually very gradual.

But what will have been the effect on the anode current of doing this? We will clearly be using a lower operating point on that curve. If we have gone too far and the operating point is on the lower bend, we can remedy this by increasing the anode potential; this will shift the anode current curve to the left * and bring our operating point to a position higher up than the bend.

When amplifying large E.M.F.'s—

(*a*) Use a greater negative potential on the grid;

(*b*) Increase the anode voltage correspondingly.

For general use, a potentiometer may be used in place of

* The grid current curve will be moved also, but a little to the right. This will further our project.

the cell C of Fig. 100. The new circuit is shown in Fig. 102. The potentiometer P is not normally necessary. One or more grid cells will suffice. The great disadvantage of the potentiometer P is that its battery B_2 is always "running down." Grid cells, on the other hand, last a long time since the current

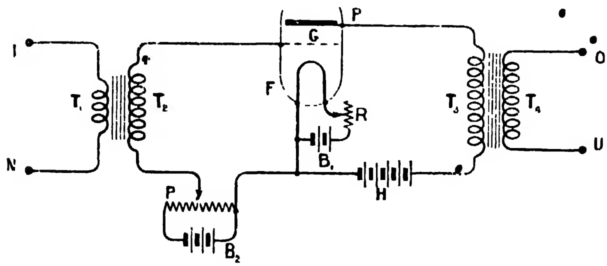


FIG. 102.—Use of potentiometer to vary the grid potential

through them is only about 1/10,000,000th of an ampere. Instead of a potentiometer a switch S may be used to bring into operation one or more grid cells (Fig. 103). A critical regulation is not necessary for amplification and so the steps of 1·5 volts each are sufficient adjustment. Fig. 104 shows

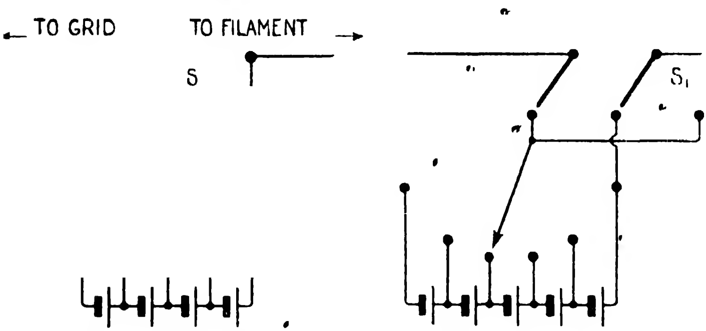


FIG. 103.—Use of grid cells in place of potentiometer.

FIG. 104. Grid battery arrangement with reversing switch.

an arrangement which may be found very useful under some circumstances. A commutator switch S_1 is provided to enable the potential applied to the grid to be made positive or negative. In both Figs. 103 and 104, a stud is provided for use when no grid cell is required.

Instead of using a cell in the grid circuit to give the grid a

negative potential the arrangement of Fig. 105 is preferable and may be used on very many circuits. The grid G is now connected indirectly to the negative side of the accumulator B, and a resistance R_1 of about 1·5 ohms is connected between the end A of the filament and the negative side C of the accumulator B. The result is that the point C has a potential of about — 1 volt with respect to A. Consequently, the grid potential is — 1 volt. The advantage of this arrangement is that the damping effect of a grid cell is avoided, although a larger accumulator may be needed. If desired the rheostat R_2 might be omitted and R_1 used as a rheostat.

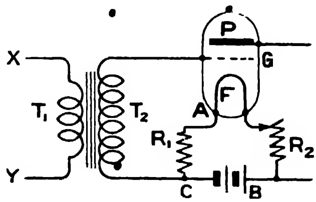


FIG. 105.—Use of resistance in filament circuit to give grid a suitable operating potential.

Graphical Representation of Amplification.—Fig. 106 shows

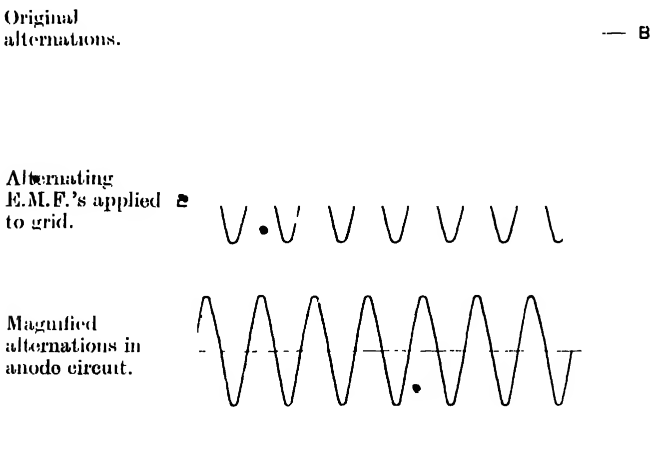


FIG. 106.—Graphical representation of amplification.

graphically what takes place when a circuit of the Fig. 102 type is used.

The top line AB shows the alternating E.M.F.'s across the terminals, I, N. These are transformed to higher E.M.F.'s

which are then impressed on the grid, which is at a suitable negative potential EF. The alternations are seen to vary the normal grid voltage EF symmetrically. The third line shows the variation of anode current about its mean value GH. These variations are large and also symmetrical. The line CD represents zero grid volts and JK zero anode current.

Use of Anode Current Resistance.—The insertion of a resistance of several thousand ohms in the anode circuit of a valve is sometimes of advantage. It has the effect sometimes of straightening the plate current curve and so lessens the distortion which may result through its non-linear characteristics.

Use of Variable Transformers.—The primary of the input transformer may with advantage be made variable in steps in order that the impedance of the primary winding may equal that of the circuit to which the amplifying valve is connected. A suitable arrangement is shown in Fig. 107. The primary T_1 of the transformer T_1T_2 is variable in four steps by means of a radial switch S_1. When the external circuit is of low resistance the first stud may be used. If the circuit to which the amplifying valve is connected is of high resistance, as in the case of the detector circuit of a crystal receiver, the switch S_1 may be placed on the top stud. This, however, affects the degree of the step-up effect also.

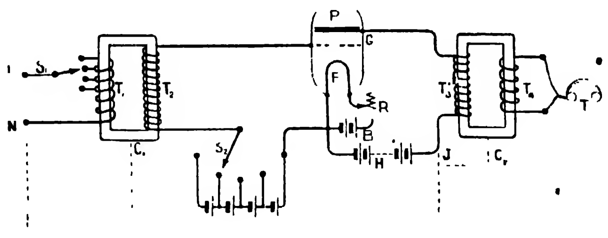


FIG. 107.—Single valve low-frequency amplifier.

Attempts may be made to resonate the various transformers to the frequency of the alternations or pulses passing through them. This may be done by connecting condensers across the windings. Iron core inductances may also be connected in series with the windings, but at present, there seems no tendency to resonate the circuits to any appreciable extent.

In the Fig. 107 circuit, the step-up ratio of T_1 to T_2 may be 1 to 10; the resistance of the primary T_1 may be conveniently

a thousand ohms and T_2 ten thousand ohms. Such figures, however, are of little value since they vary very considerably in different amplifiers.

The figure also shows the grid cell switch S_2 in use.

The energy drawn from the anode circuit by means of the transformer T_3T_4 is being used to actuate the telephone receivers T. The arrangement constitutes a telephone transformer and its use is always preferable to connecting the telephones directly in the anode circuit. The winding T_3 should be of a high resistance approximating to the resistance of the valve between filament and anode. If wound with copper wire a resistance of about 5,000 ohms will be suitable for T_3. The winding T_4 should have the same resistance as the telephones. This may conveniently be 120 ohms. The transformer ratio of T_3T_4 may conveniently be 5 : 1.

Type of Amplifier Transformers.—The transformers of Fig. 107 are of the closed-core type. Closed-core transformers have been found the more efficient although the open-core type is probably the best for amplifying speech. There is less hysteresis in the open-core transformer, and, although the amplification may not be so great, yet there is less distortion of the waveform of the currents to be amplified.

The cores of the transformers are preferably built up of wires or plates made of a special form of soft iron known commercially as "Stalloy."

Special Connections.—The operation of the valve as a low-frequency amplifier is generally improved by connecting the cores C_1 and C_2 of the transformers T_1T_2 and T_3T_4 to the positive side J of the anode battery H. This materially lessens the parasitic noises which frequently accompany the operation of an amplifier employing transformers. These noises are usually traceable to leakages in the batteries, the unsteady current from an accumulator or anode battery, transformer leakages, various capacity and inductive effects, peculiarities of valves, microphonic effects produced by vibration of the valve, and numerous other causes. Many of these noises may be prevented by careful insulation of all batteries and apparatus. Care should be taken that none of the leads cross, as otherwise complications due to induction may arise. They should be short and should not be near any earth-connected conductors. The component parts of the vacuum tube amplifier should preferably be placed well apart.

Another special connection which will help to silence undesirable noises is that from the input terminal N to the point J.*

Use of Auto transformers.—The input transformer may, if desired, consist of one winding. Auto-transformer effects are then used and may be employed to step-up the incoming

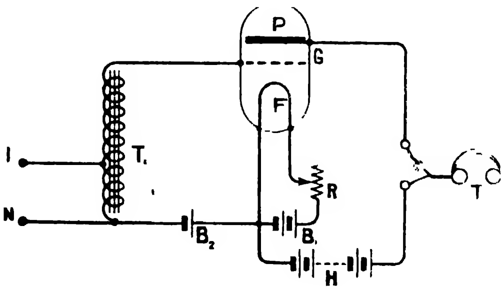


FIG. 108.—Use of auto-transformer in a L F. amplifier.

E.M.F.'s. An example of the use of an auto-transformer is illustrated in Fig. 108. This is rarely done.

Use of Resistances in Place of Transformers.—A transformer needs careful construction and more careful design. We may, however, get amplification effects without a transformer at all, and the principle of Fig. 109 may be utilised

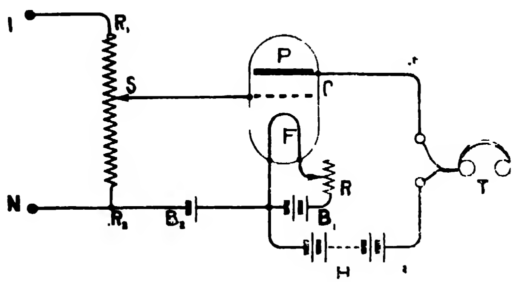


FIG. 109.—Showing use of a resistance in an amplifier.

to a large extent in the design of vacuum tube apparatus. The resistance R_1R_2 may be a non-inductive resistance of, say, 10,000 ohms. There will be a potential drop along R_1R_2 when a current is flowing. Tappings may be taken from different points along R_1R_2 by means of the switch S. The input

* Condensers across the transformer windings sometimes make the amplifier operate more silently.

current flowing through R_1R_2 causes the potential across S and R_2 to vary. The potential of the grid will, therefore, be altered with respect to the filament, and the current variations amplified in the anode circuit. The strength of the current variations in the anode circuit may be varied by altering the position of S. The maximum effect is obtained when the grid and filament are connected across the whole of the resistance R_1R_2.

The advantage of using a resistance, apart from simplicity, is the fact that it offers the same resistance approximately to currents of any frequency. One disadvantage is that we miss the valuable stepping-up effect obtainable by means of a transformer.

The resistance type of amplifier shown in Fig. 109 may be employed in cases where a transformer amplifier is quite useless. Such is the case when we desire to produce an amplification effect by means of a direct current. An example is given in Fig. 110. A distant telegraph transmitting station consists of a battery B_3 and a tapping key K. Two long line

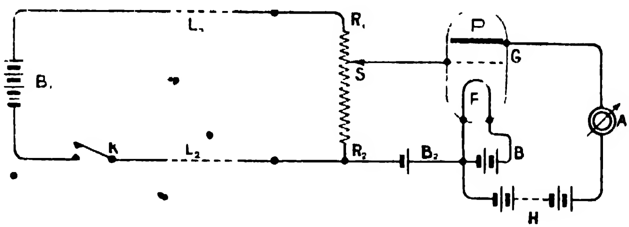


FIG. 110.—Use of a resistance in an amplifying circuit for direct current.

wires L_3, and L_2 connect the transmitting to the receiving station, which latter has a resistance amplifier with a milliammeter A giving, say, a normal reading of 1 milliamp. On depressing the key K an electron current flows round the circuit $B_3KL_2R_2R_1L_3B_3$, producing a steady potential difference between S and R_2 which causes the anode current to rise to, say, 5 milliamps. The milliammeter A will, therefore, remain at 5 milliamps. as long as the key K is depressed. A relay might replace A. The spring which keeps the arm of the relay in place might be tightened so that the steady current in the anode circuit just failed to close the contacts of the local circuit. On depressing the key K the increased anode current would close the contacts.

A Simple Amplifier of Rectified Pulses.—Fig. 111 shows a simple circuit in which a valve is acting as an amplifier of the rectified pulses obtained from a crystal detector D. Pulses of potential are impressed on the grid G of the valve and

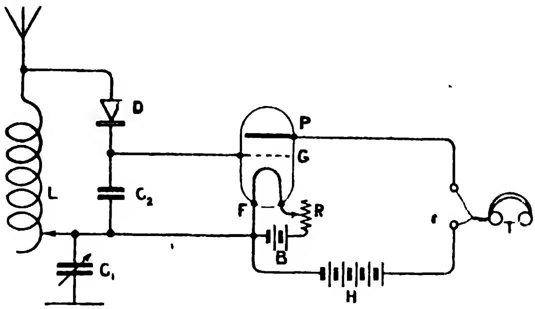


FIG. 111.—Use of valve as an amplifier of rectified pulses from a crystal detector

amplified in the anode circuit, giving signals perhaps 5 times as strong as those which normally would be obtained without the valve.

A better circuit, but a more complicated one, for use with a crystal detector is that shown in Fig. 112. The primary winding of a step-up transformer is connected across the

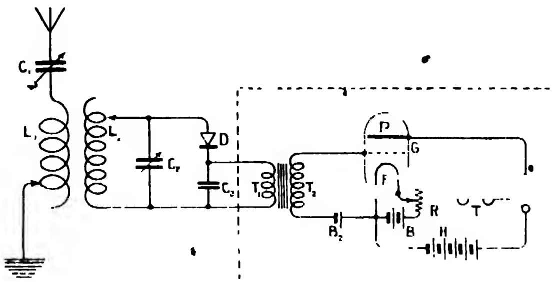


FIG. 112.—Application of L.F. amplifier to crystal detector circuit.

terminals where normally the telephone receivers would be connected. The impedance of this primary winding should be as high as possible, since the resistance of the detector is very high. The E.M.F. of the unidirectional pulses is stepped-up before being applied to the grid of the valve.* The condenser

* The potentials applied to the grid will be alternating.

C_3 may sometimes be omitted. The complete arrangement enclosed by the dotted rectangle, consisting of a one-valve amplifier, may be connected up as a separate instrument which could be readily applied to any kind of a circuit.

The connections from the terminals of the condenser C_3 of Fig. 112 to the grid and filament of the valve, should be reversed when first joining up the circuit, in order to see which way round gives the loudest signals. A certain way round sometimes gives the best results.

Amplification of Oscillations.—So far we have considered circuits using the vacuum tube as an amplifier of low frequency current variations. It may, however, be used equally well as a magnifier of oscillations of very high frequency. Owing to the great mobility of the electrons, oscillations having a frequency as great as thirty millions per second may be faithfully reproduced on a larger scale in the anode circuit of a valve.

If we arrange a circuit similar to that of Fig 113, we will amplify incoming oscillations. By the use of a grid cell B_2

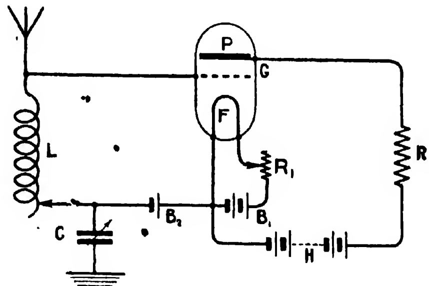


FIG. 113. Circuit for high-frequency amplification.

(or equivalent arrangement) and suitable values of filament current and anode voltage, we can ensure that the oscillations flowing in the anode circuit PRH are of exactly the same waveform as the original oscillations, and are not in any way rectified. These amplified oscillating currents flow through the resistance R included in the anode circuit and may be used in a variety of ways. We might for example connect a high-resistance crystal detector and telephones across the resistance R. Instead of R we might use an inductance tuned or aperiodic.

It has already been shown that the rectified current obtained

by using a bend in a characteristic curve is proportional to the square of the amplitude of the incoming waves. The action of a crystal detector may be explained by the non-linear characteristics it possesses, so that weak oscillations produce a smaller relative effect than strong ones. It is therefore very desirable to increase the amplitude of oscillations artificially before rectifying them.

Fig. 114 shows a practical circuit in which the oscillations are first amplified and then rectified.* In the anode circuit of the valve is included a fixed inductance L_2 through which the magnified oscillations pass. No attempt is made to tune the coil L_2. It is therefore *aperiodic*. It allows oscillations of all frequencies to pass through it. The frequency of the

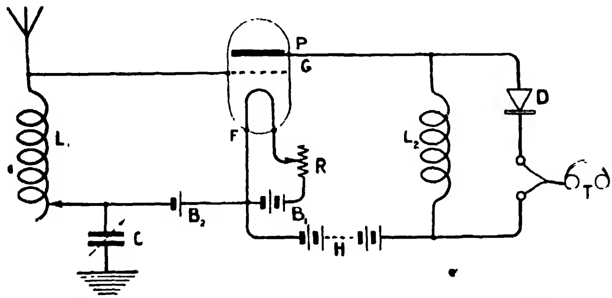


FIG. 114.—Showing the oscillations amplified by a vacuum tube before being rectified.

oscillations in L_2 will equal the frequency of the E.M.F.'s on the grid, that is, the frequency of the incoming waves, even if the natural wave-length of L_2 is not in tune. In the latter case the oscillations in L_2 will be *forced oscillations*. To make the coil aperiodic the turns should be spaced well apart to prevent the coil possessing too much self-capacity. It may be wound with resistance wire. Such aperiodic inductances are very frequently used in the anode circuits of valves as they require no tuning. They possess a natural wave-length which should be made less than the lowest wave-length to be used.

Having now obtained amplified oscillations in the inductance L_2, we require to rectify them. This may be accomplished by connecting a "perikon" crystal detector D and a

* The Gesellschaft für Drahtlose Telegraphie appear to claim H.F. amplification followed by rectification in British Patent 8821/13 (April 15/13).

pair of telephone receivers T across the inductance L_2. Loud signals will be heard in the telephones. Such a circuit is far more scientific and successful than the type shown in Fig. 111. High-frequency amplification followed by rectification is usually greatly preferable to rectification followed by low-frequency amplification, especially when only one valve is used.

If we desire to do so, we can *tune* the *anode oscillatory circuit*. Rather better results are obtained when the anode circuit is tuned to the same frequency as the oscillations, especially when incoming signals are weak. Fig. 115 shows a condenser C_3 connected across the inductance L_3, which is now variable in steps or by means of a sliding contact. A potentiometer P is shown in the circuit for use with the crystal detector if

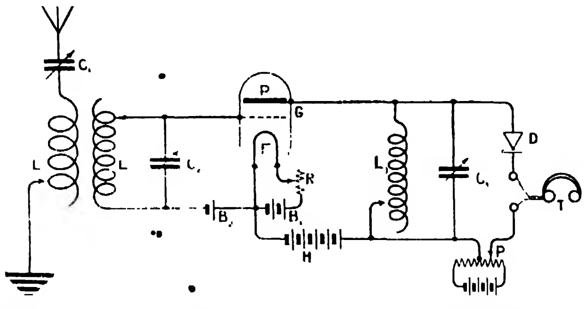


FIG. 115.—H.F. amplification circuit with tuned plate circuit

the latter requires it. If carborundum crystals are used a potentiometer will be necessary.

The anode oscillatory circuit now consists of the inductance L_3 and the variable condenser C_3. It should be tuned to the frequency of the incoming oscillations. If out of tune, it will not act as did the aperiodic coil L_2 of Fig. 114. Signals will be weaker or inaudible.

The circuit of Fig. 115 needs a considerable amount of adjustment since the anode oscillatory circuit sometimes called the "tertiary" circuit, requires tuning in addition to the aerial circuit L_1C_1 and the closed circuit L_2C_2.

To obtain finer tuning than that obtainable on the circuit just described, we may connect the detector circuit across a separate oscillatory circuit coupled to the anode oscillatory circuit. A suitable arrangement is shown in Fig. 116. The

various processes involved will perhaps be more clearly shown by this figure. The magnified oscillations taking place in L_3C_3 set up similar oscillations in the circuit L_4C_4. If the coupling between L_3 and L_4 is loose, much undesirable jamming may be eliminated. Needless to say, the circuit is rather difficult to tune and needs the full attention of an experienced operator. It is not, therefore, adaptable for use when an operator desires to change his receiving wave-length rapidly. Matters may be considerably improved by having a table showing the values of inductance L_2 and capacity C_2 which give the circuit a certain wave-length. Similar cards may be made out for L_3C_3 and L_4C_4. If it is desired to receive a certain wave-length, these three circuits can be adjusted immediately. It is then only necessary to listen-in by varying the tuning of the aerial circuit. If the coils L_2, L_3 and L_4

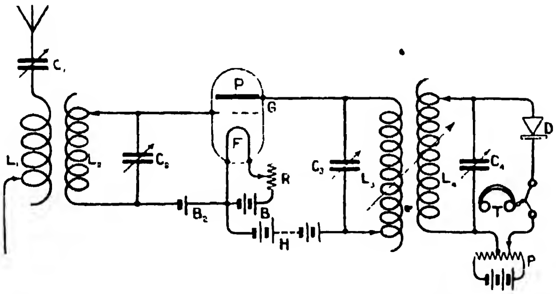


FIG. 116.—Showing detector circuit loosely coupled to plate circuit of valve acting as H.F. amplifier.

and the condensers C_2, C_3 and C_4 are all the same size, a rubber band may be passed round the handles of the three condensers, so that on turning one condenser, the others turn the same amount. This may be done on certain condensers and facilitates tuning. If desired the tertiary circuit L_3C_3 may be made aperiodic, but the circuit L_4C_4 should preferably be carefully tuned. A complex switch might be used to vary L_2, L_3, and L_4 simultaneously.

A single valve may be used not only to amplify the high-frequency oscillations but also to magnify at the same time the rectified pulses obtained from a crystal detector.* A circuit in which this occurs is given in Fig. 117. Oscillations set up

* See British Patent 8821/13 (April 15/13), of Ges. für Drahtlose Telegraphie.

in the circuit L_1C_1 cause magnified oscillations in L_2C_3, which are rectified by the crystal detector D. The rectified pulses pass through the primary T_1 of a step-up transformer T_1T_2, the secondary T_2 of which is connected in the grid circuit of the valve. The E.M.F. of the pulses is stepped-up and applied to the grid, causing large variations of grid potential at audio frequencies. These low-frequency pulses are thus changed to alternating current and amplified in the anode circuit, where they are detected by the telephones T. We have then in the anode circuit radio-frequency variations superimposed on audio-frequency variations. The condition of affairs is, therefore, somewhat similar to that existing when a grid condenser is used (see Fig. 96). The blocking condensers C_2, C_4 are used to provide an easy by-path for high-frequency oscillations.

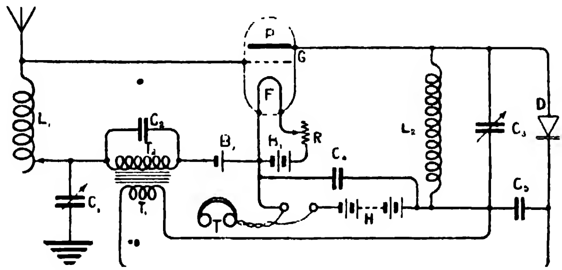


FIG. 117.—Single vacuum tube arranged to act as an amplifier of high-frequency and low-frequency currents at the same time.

Many variations of the Fig. 117 circuit may be devised. The reader himself may make up endless combinations of the various circuits already given, which are mostly typical. It is the object of the author to show the principles involved. Once these have been mastered, the reader is almost independent of text-books He will be able to design circuits to meet his own requirements or resources.

The crystal detector has been found almost as sensitive as the three-electrode vacuum tube when the latter is used as a pure rectifier. It has therefore been frequently adopted when rectification is desired. This class of circuit, however, is not very easy to adjust, and simple circuits employing additional tubes are probably to be preferred. Moreover, the unreliability of crystals is notorious, and their use in valve circuits is now very limited.

CHAPTER V.

RETROACTIVE OR REGENERATIVE AMPLIFICATION.

Retroaction. We have just seen how incoming oscillations may be magnified by means of a vacuum tube. What perhaps is a still more interesting method of increasing the amplitude of these oscillations is what is known as *retroactive* * amplification; sometimes it is called "regenerative" or "reaction" amplification.

The essential principle of this system consists in making the amplified oscillations in the anode circuit of a valve retroact (*i.e.* act back) on the grid circuit and so reinforce the *original* E.M.F.'s on the grid, resulting in a building-up effect.

One method of obtaining this effect is shown in Fig. 118.

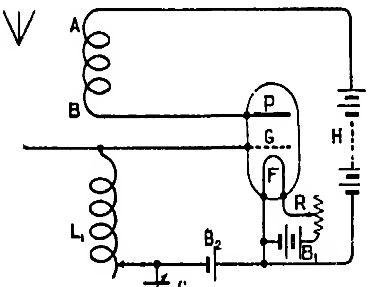


FIG. 118.—Circuit in which retroaction is obtained.

Incoming oscillations in L_1 vary the grid potential on either side of its normal value. The anode current flowing through the aperiodic inductance coil AB is varied at a radio frequency exactly in time with the oscillations in L_1. We have then in AB stronger oscillations than those in L_1, owing to the amplifying action of the tube. They will, however, have the same frequency and about the same degree of damping as those in L_1. Now if we couple the coil AB, which may be called the *retroactor coil*,† to the inductance L_1, it will induce oscillations in L_1. Since oscillations are already taking place in L_1, they will combine with the induced oscillations and produce still stronger currents in

* A term originally used by W. H. Eccles.

† Also known as "reaction coil" or "reactance."

L_1. This assumes, of course, that the induced oscillations are in phase with the original oscillations.

If the field of the coil AB is arranged so as to assist the magnetic field of L_1, retroactive amplification is obtained. If the field of AB be opposed to that produced around L_1 by the original oscillations, not only will there be no amplification, but there will actually be a tendency to prevent any oscillatory current flowing in L_1. Incoming oscillations are then usually said to be *absorbed*. The field produced by the coil AB may be reversed by reversing the coil; the same result may be obtained by reversing the connections to the ends A and B of the retroactor.

If the coil AB is not reversible, it is necessary in order to obtain retroactive amplification that the connections to A and B should be correct. The reason is fairly obvious. The retroactor AB induces E.M.F.'s in the coil L_1, which cause the grid to be positive one moment and negative the next. If the induced E.M.F. on the grid is of the same sign as that which the original oscillations are placing on the grid at that particular moment, the two effects will combine and cause a still larger variation of current in the anode circuit. If, on the other hand, the induced grid potential is of opposite sign to that which is produced by the original oscillations, the two effects will tend to neutralise each other.

The degree of coupling between AB and L_1 is of great importance. If the retroactor is connected the right way round, the closer it is to L_1 the greater will be the retroactive amplification effect obtained. If AB is turned at right angles to L_1 the mutual effect will practically be nil. On turning AB still further round past 90°, the oscillations induced in L_1 by AB will oppose those already taking place there and may completely destroy them.

Some Theoretical Aspects of Retroaction.—The action of the coil AB on the oscillations in L_1 may perhaps be more clearly understood by considering the action of an ordinary pendulum. If a weight be suspended by a cord and after being drawn to one side be released, it will swing to and fro and finally come to rest. The oscillations of the pendulum are damped; that is to say, each succeeding oscillation has a smaller amplitude than the one before it. The reason why the pendulum comes to rest is because the friction at the point of support and the resistance of the air combine to dissipate the energy of the

oscillations, which consequently die out. If we lessen the resistance offered to the oscillations by enclosing the pendulum in a vacuum and, by carefully suspending it, a considerably longer time will elapse before the oscillations die out. An analogous case is that of electrical oscillations flowing in a receiving circuit. An important reason for the damping of received signals is the resistance of the receiving circuit. A group of damped waves usually dies out after about 25 complete oscillations, corresponding to a logarithmic decrement of 0·2. If each oscillation occupies 1/1,000,000th of a second, as it would in the case of waves of 300 metres length, the time occupied by one complete wave-train would be 25/1,000,000th or 1/40,000th of a second. This is a very short time for the wave-train to produce an effective response in the detector circuit. Any arrangement which will prolong the duration of the wave-train will increase its energy and capability of doing work, and will consequently cause an increase in the strength of signals obtained.

By using the valve as an amplifier of the high-frequency oscillations, the amplitude of the latter is increased very considerably. The use of the valve in this way, however, does not affect the duration of the wave-train; the damping of incoming oscillations is hardly affected. How can we affect the damping of the oscillations of the pendulum? We can lessen the resistance offered to the pendulum, but only to a certain extent. Friction cannot altogether be obviated. We can, however, supply energy from outside which will compensate for the loss sustained through friction and other causes. We can, for example, give the pendulum a slight tap at the end of each swing. If the tap is large at first and gradually decreases, the pendulum will swing for a very much longer period, but in the end will come to rest. If, however, the taps are sufficiently strong to compensate completely for the dissipation of energy, the pendulum will continue to swing indefinitely. Such *sustained* oscillations take place in watches and clocks. The pendulum is made to oscillate continuously by properly timed taps given by the mainspring through the escapement, the timing being accomplished by the pendulum itself.

Turning now to our retroactive circuit of Fig. 118, we see that it will act like the escapement of a clock. By means of the coil AB, correctly timed impulses are given to the oscillations in L_1. These impulses have the effect not only of

strengthening the oscillations in L_1, but also of lessening their damping. The impulses given may be strengthened by tightening the coupling between AB and L_1. When they completely compensate for the energy losses in the receiving circuit, the oscillations in L_1 become sustained and will continue even if no signals from outside are being received. The valve is now generating oscillations of its own accord, the energy being supplied by the anode battery H. The oscillations in L_1 cause amplified oscillations in AB which strengthen the oscillations in L_1. The process of building up the oscillations in L_1 is repeated until a state of equilibrium is reached which depends on various factors which will be discussed later. The oscillations in AB and L_1 support [illegible]ther, and the valve may be said to be in a state of *self-oscillation*. A somewhat similar phenomenon is noticed when a microphone and telephone are placed opposite each other and connected as shown in Fig. 119. The microphone M picks up a noise which it passes on to the telephone receiver T, which in turn sends out sound waves which affect the microphone; the process is then repeated. By placing the ear near to T a continual buzzing will be heard, which, however, ceases when T and M are separated.

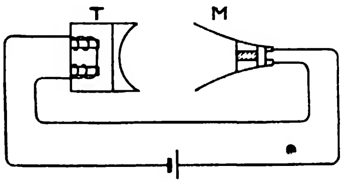


FIG. 119.—A microphone and receiver retroactively coupled to produce buzzing.

The phenomenon of self-oscillation is of exceedingly great value, but at the present moment we are only interested in the stages which precede the state of generation. When the value is adjusted to what we will call a "pre-oscillatory" condition, incoming oscillations are greatly magnified and the resultant signals are increased to a value five or six times as great as that obtained when retroaction is not used. Since the oscillations are already amplified in the ordinary way, the total magnification obtained is about thirty times. Retroactive amplification is therefore of great use when dealing with very weak incoming oscillations.* They are developed and strengthened until they are capable of giving loud signals when applied to a detector circuit.

* Weak signals are always strengthened to a greater extent than strong ones by retroaction.

Another advantage of using retroactive amplification is that, since the waves are less damped, much finer tuning is obtained and less interference from other stations using different wave-lengths, is experienced.

Graphical Representation of Retroactive Amplification.—The additional amplification obtainable by means of a coupling arrangement between anode and grid circuits is shown graphically in Fig. 120. The top line shows two groups of the original oscillations. These are first amplified as shown in the second line. The damping remains the same. If now we couple the anode circuit to the grid circuit in a suitable manner, the magnitude of the oscillations in the latter circuit will be

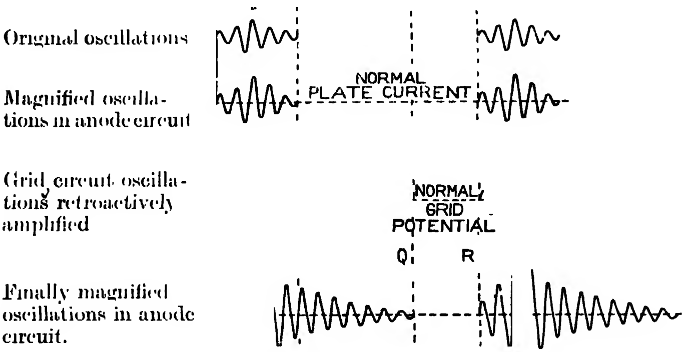


FIG. 120.—Graphical representation of retroactive amplification.

strengthened and the oscillations will die out more gradually. In the ordinary way, they would probably die out at the point P, at the conclusion of the wave-train. By using a suitable coupling between the retroactor AB and the inductance L_1, the oscillations will continue up to, say, a point Q. The effect of this varying grid potential will be to cause similar variations in the anode current as shown in the bottom line.

The extent to which the damping is decreased may be varied by means of the coupling between AB and L_1. The tighter the coupling, the nearer will the end of the first group of oscillations be to the beginning of the next. The space between groups of oscillations is very great and may be about twenty to forty times the actual duration of each group. We have therefore plenty of time in which to prolong our wave-

train before encroaching upon the next one. The more we prolong the train of oscillations, the greater will be its energy and the greater will be the final effect in the telephones. We should endeavour to prolong it to such an extent that it dies out just before the next wave-train commences. If we tighten the coupling too much we will have the effect shown in Fig. 121. The first group of oscillations has not died down before the next one arrives. The result is that the two groups of oscillations merge into each other.

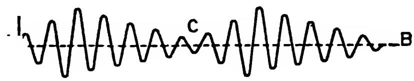


FIG. 121.—Effect of increasing the retroaction too far.

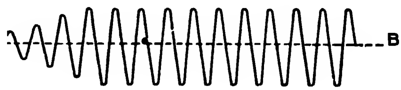


FIG. 122.—Retroaction still further increased, producing self-oscillation.

When the groups are rectified there will only be a small change in the current flowing through the telephones. When the coupling is tightened still further, the oscillations do not die down at all, but persist. This is shown in Fig. 122. If these continuous oscillations are rectified, only a steady current will normally flow through the telephone receivers.

Receiving Circuits employing Retroaction.—We have seen how weak oscillations may be greatly strengthened by means of a retroactive coupling. It now simply remains to rectify these magnified oscillations. A suitable circuit for doing this is given in Fig. 123.

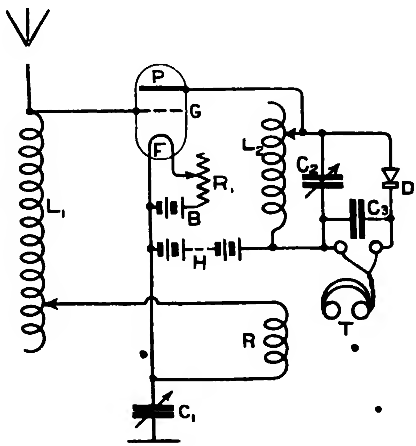


FIG. 123.—Retroactive amplifier of oscillations which are afterwards rectified by a crystal detector.

The aerial circuit consists of an inductance L_1, having in series with it a small coil R and a variable condenser C_1. The

E.M.F.'s produced at the top of L_1 and the bottom of R are placed across the grid and filament of an amplifying valve. The oscillations are amplified in the anode circuit. In series with the anode battery we have an inductance L_2 shunted by a variable condenser C_2. The anode oscillatory circuit is therefore a tuned one, and not aperiodic as was the case in Fig. 118. Rather better results are obtained by having the anode circuit tuned. Across the condenser C_2 is connected the usual detector circuit which rectifies the oscillations taking place in L_2C_2. The small coil R is coupled to the inductance L_2, and by this means the oscillations in L_2 are able to act back on the original oscillations.

The reader should not be confused by the various arrangements he will see in this volume and elsewhere. There is usually a practical reason for slight variations in the actual arrangement of parts of the circuit. The Fig. 123 circuit is specially adapted for use with long waves. It is obviously inconvenient to couple a large inductance like L_2 to the main inductance L_1. It is a better arrangement to use a small coil like R, which may easily be revolved inside a tube on which L_2 may be wound.

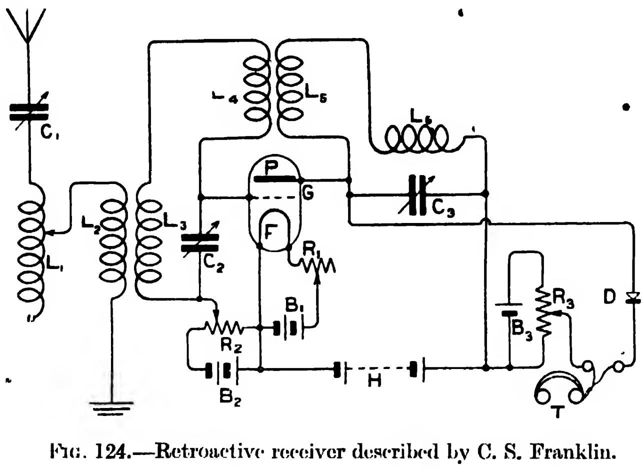


FIG. 124.—Retroactive receiver described by C. S. Franklin.

Franklin's Retroactive Circuit.—C. S. Franklin and Marconi's W. T. Company have in British Patent 13,636/13 (June 12/13) described a method of receiving signals employing retroactive amplification. This is shown in Fig. 124. In this

case a portion L_4 of the grid oscillatory circuit is coupled to a coil L_5, which is part of the anode oscillatory circuit. This saves having to couple the two large coils L_3 and L_6. The potentiometer R_2 serves to give the grid a suitable potential. The other potentiometer R_3 is used to adjust the crystal detector D to its best point of operation. Signals are produced in the telephones T. This circuit, when simplified, is a modification of Fig. 123. The question of priority of invention with regard to retroactive amplification has been much debated, other inventors, such as E. H. Armstrong, claiming priority.*

Arco and Meissner's Circuits.—In British Patent 252/14 (Jan. 5/14), Arco and Meissner describe a method of amplification which employs retroaction. Their circuit is reproduced in Fig. 125. The variable current to be amplified, *e.g.* incoming oscillations, is made to pass through the coil 6. Similar oscillations are set up in the coil 8 and thereby influence the grid 4 of the vacuum tube. Amplified oscillations are produced in the anode circuit, which includes the anode 3, a coil 11, another coil 12, and a source of potential 10, which may be a dynamo or battery. The oscillations in 12 are made to act back on the oscillations in 8, thus effecting retroactive amplification. The amplified energy may be drawn from the coil 11.

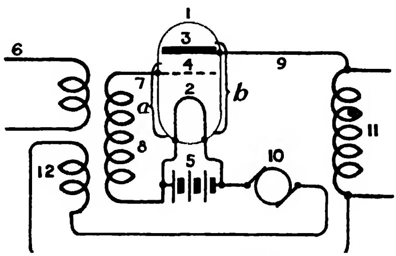


FIG. 125.—Arco and Meissner's arrangement.

The principle of Fig. 125 is applied by Arco and Meissner in the Fig. 126 circuit, which they proposed to use for the reception of wireless signals. Incoming oscillations passing through 14 induce oscillations in the closed circuit 16, 17, which is tuned by means of the condenser 17. The grid oscillatory circuit is coupled to the closed circuit at 8. The oscillations having thus been passed on twice, are made to influence the grid 4, and cause amplified oscillations in the anode circuit which is coupled at 12 to the closed circuit, thereby

* E. H. Armstrong claims retroactive amplification in British Patent 147042 (Oct. 29/13). He has proved in American Courts documentary evidence, dated Jan. 3/13, describing his invention. This date is earlier than Franklin's.

amplifying by retroaction the oscillations flowing in that circuit. It should be noticed here that the oscillations in the anode circuit may, with practically equal efficiency, be caused to react on the aerial circuit, closed circuit, or grid oscillatory circuit. For example, the coil in the anode circuit of Fig. 126 might be made to retroact on the coil 14, the coil 16 or coils in that circuit, or the grid inductance. Having amplified their incoming oscillations, Arco and Meissner proceed to detect them by connecting a crystal detector 19 and telephones 21 across a portion of the closed circuit. Although it is more usual to connect the detector across the whole of the inductance in a circuit, the Telefunken Company (of which Arco and Meissner are engineers) invariably prefer to connect it across only a portion of the inductance. Their idea, which is certainly effective in practice, is that the loss of E.M.F. across the detector by connecting it across only a portion of the inductance is more than compensated by the fact that the damping effect of the detector on the oscillations is thereby made less. The variable tapping shown on the coil 16 will therefore not confuse the reader. It may be as well to point out another generalisation: the detector circuit might be connected, with equal effect, across the grid oscillatory circuit or across the inductance included in the anode circuit. The latter arrangement is generally to be preferred.

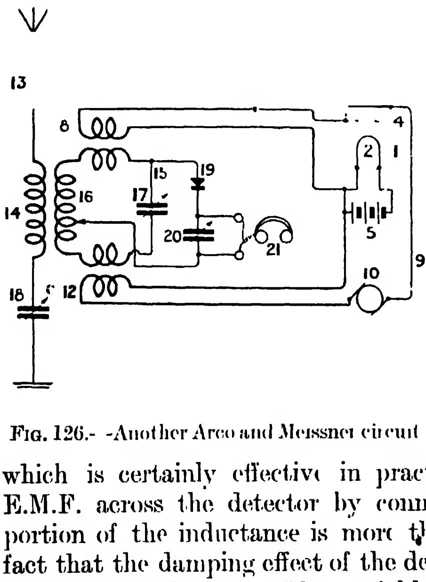


FIG. 126.—Another Arco and Meissner circuit

Another circuit described by Arco and Meissner which interests us at present is that of Fig. 127; there the incoming oscillations induce into the closed circuit 8 and so cause amplified oscillations in the coil 11. This coil is coupled to a circuit 16, 17, which includes a small coil which retroacts at 12 on a portion of the grid oscillatory circuit, which this time is the secondary receiving circuit. The detector circuit 19, 20 and 21 is connected as usual. The anode oscillatory current only retroacts

in this case after passing through two coupling arrangements. A circuit might be designed where it only acted on the original oscillations after a dozen couplings; the principle would still be the same, and the reader who is a student should realise this once and for all; otherwise the circuits he will meet with will always present difficulties.

The circuits of Arco and Meissner are object lessons, as they

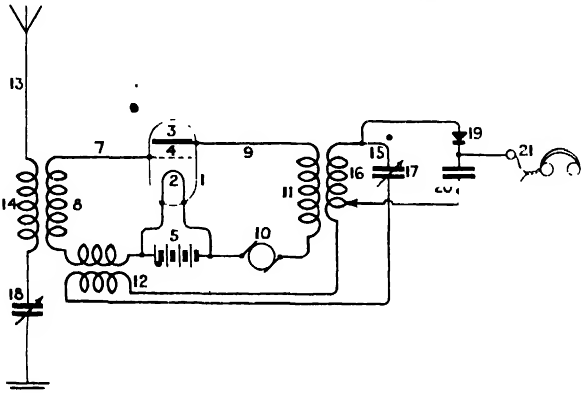


FIG. 127.—Another circuit described by Arco and Meissner.

show what different circuits may be arranged using the basic circuit of Fig. 118. They were designed originally for use with the Lieben-Reisz soft vacuum tube relays, but are equally suitable for use with modern types. Lower anode voltages may be used and a battery employed instead of a D.C. generator.

Special Circuits.—We will now consider a number of retroactive circuits utilising a valve as a retroactive amplifier and a crystal detector as a rectifier. An example of this type of circuit is given in Fig. 128. The potential of the grid is varied by moving a sliding contact along a resistance R_2 connected across the filament heating battery.* The condensers C_3 and C_4 are connected across parts of the circuit which would act as impedances to high-frequency currents. A step-down transformer T_1T_2 and low-resistance 'phones T are connected in the detector circuit. A resistance r was included in the anode circuit when valves of the soft type were used. The circuit will, however, work excellently with modern vacuum tubes without this resistance.

* This usually has no advantage in case of modern valves

A further development of the Fig. 128 circuit was to bring the detected current back into the grid circuit and so amplify it. This "double-magnification" circuit, which is exceedingly

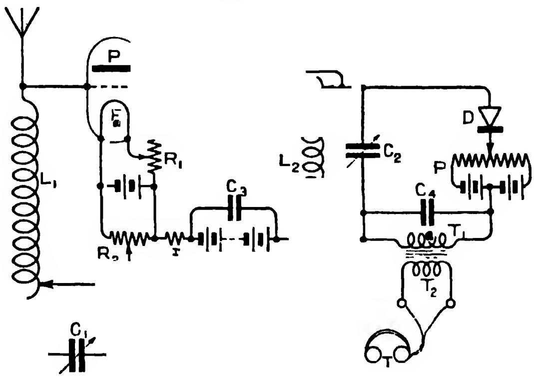


FIG. 128.—Retroactive circuit using crystal as rectifier.

sensitive, is shown in Fig. 129. The oscillations passing through L_1 and R impress high-frequency E.M.F.'s, through C_3, on to the grid. Magnified oscillations are produced in the

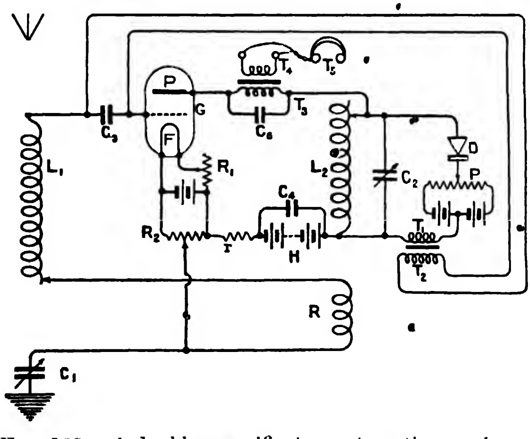


FIG. 129.—A double-magnification retroactive receiver.

anode oscillatory circuit L_2C_2. These are rectified by the detector D. The rectified current passes through the primary T_1 of a step-up transformer T_1T_2. The pulses of potential are conveyed from the secondary T_2 to the grid circuit and so cause audio-frequency variations of grid potential. These

variations are magnified by the vacuum tube and pass through the primary T_3 of a step-down telephone transformer T_3T_4, the secondary terminals of which are connected to a pair of low-resistance 'phones T_5. The windings T_2 and T_3 do not affect the high-frequency oscillations which take the shunted and easier paths through the condensers C_3 and C_6.

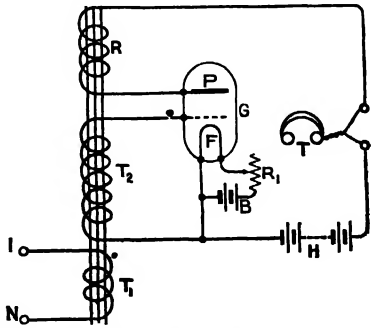


FIG. 130.—Retroactive amplification of low-frequency currents.

Low-Frequency Retroaction.*—The benefits of retroaction are not confined to high-frequency currents. Fig. 130 shows an arrangement by which low-frequency current variations may be strengthened. The current to be magnified is passed through the winding T_1. The voltage is stepped up in T_2. The amplified current variations in the anode circuit are passed round the winding R and retroact on T_2. If the coupling effect between R and T_2 is made too great the valve will oscillate of its own accord at a low frequency which, if within the audible range of the human ear, will produce a buzz.

Low-frequency retroaction was suggested by S. G. Brown for use with his special two-electrode amplifier.†

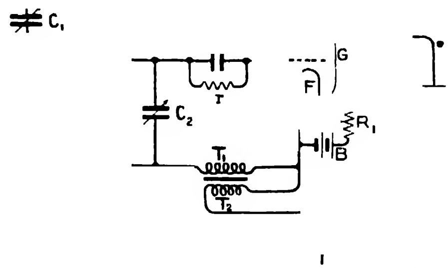


FIG. 131.—Circuit in which low-frequency impulses are retroactively amplified.

An example of low-frequency retroaction is given in Fig. 131, which shows how rectified pulses in the anode circuit of a valve may be re-amplified. A condenser across T_1 may be added.

Detection and Amplification in the one Valve.—The

* Taken advantage of in British Patent 3950/15 of L. de Forest.
† See p. 53.

disadvantage of the circuits we have been describing is the difficulty of adjusting the crystal detector. This is frequently a source of trouble, especially when there is vibration, as in an aeroplane. Something more robust and needing less attention is desired by most operators. The use of crystals has therefore fallen largely out of favour. This has been caused by the introduction and development of circuits in which only valves are used.

This development appears to be chiefly due to E. H. Armstrong, of U.S.A., who was one of the first to make one vacuum tube carry out various duties at the same time.

Marconi's Wireless Telegraph Company, and H. J. Round, obtained British Patent 28413/13 (Dec. 9/13) for an arrangement which has been very extensively used. Fig 132 shows the arrangement, which is intended for the reception of continuous waves but might be used for the reception of spark signals by means of retroactive amplification although this use is not described.* Incoming oscillations are induced into the grid oscillatory circuit *a*. Magnified oscillations are set up in the tuned plate oscillatory circuit *e*. The potential of the grid is adjusted by means of a potentiometer arrangement, and the anode battery and the filament current regulator are also adjusted so that the valve is being used at one of the bends on its anode-current curve, or preferably, on the bend of the grid-current curve. Rectification is produced, and the signals are detected by the telephones. We have, therefore, in the anode circuit high-frequency current variations superimposed on the audio-frequency variations. The radio-frequency component of the anode current does not affect the telephones. A condenser of about 0 001 mfd. is usually connected across the telephones, and

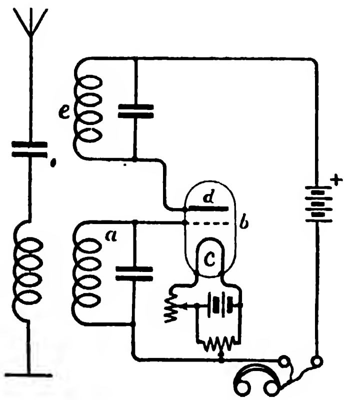


FIG. 132.—Showing a valve used simultaneously as a detector and retroactive amplifier.

* The patent claims means for receiving continuous waves by detuning circuit *e*.

sometimes also across the anode battery, to allow a readier path for these high-frequency current variations. If the condenser is not used, the capacity of the cords and windings of the telephones affords a fairly good path. The high-frequency component, however, sets up oscillations in the anode oscillatory circuit which retroacts, by virtue of the magnetic coupling between *e* and *a*, on the grid oscillatory circuit *a*. The coupling is so adjusted that the circuit just fails to oscillate of its own accord. The oscillations in *e* are then considerably strengthened, the rectification is greater, and the signals in T are louder. If desired, the circuit *e* may be coupled to the aerial circuit with equal effect.

In arranging a circuit of this type, the retroactor may conveniently be placed at one end of the cylindrical inductance in the grid circuit. The retroactor may be revolved about its axis or may slide in and out of the inductance in the grid circuit. At the other end of the grid coil may be placed the aerial coil, which in a similar way may revolve or slide in and out. It will usually be more convenient to use a small coil for this purpose, in series with a variable aerial tuning inductance.

It has been suggested that rectification on this circuit may be accomplished by using one of the bends of the anode characteristic curve. There is a disadvantage in doing this. Although the rectification may be good, the amplification will be small and the radio-frequency oscillations in the anode circuit will be of small amplitude. It is therefore probably better on this type of circuit to use grid current rectification by adjusting the potential of the grid to the bend on the grid-current curve. This effect may be obtained by simply connecting the grid, *viâ* the grid circuit inductance to the negative end of the filament. A grid condenser may also be used to obtain a cumulative effect. When these grid-current rectification methods are employed, an operating point on the straight steep portion of the anode curve may be used, and strong amplification of the radio-frequency component is obtained.

Effect of Asymmetrical Retroaction.—It is to be noticed that when rectification is taking place, the radio-frequency component does not consist of uniform sinusoidal oscillations. When rectification is obtained by means of grid currents, or by adjusting the valve to a point on the saturation bend, the normal value of the anode current falls and the negative half-oscillations are magnified to the greater extent. This is

clearly shown in Fig. 96. Only when the valve stops rectifying, do the half-oscillations become uniformly amplified. Since the negative half-oscillations in the anode circuit are more developed than the positive half-cycles, the retroactive effect of the former will be the greater. When a negative half-oscillation is flowing in the anode circuit a negative half-oscillation of the incoming signals will be taking place in the grid oscillatory circuit. The two effects, therefore, help each other. The effect, then, of retroaction in a circuit like this is not just to strengthen and prolong the incoming wave-train, but to *accentuate* the difference in amplitude between positive and negative half-cycles. If the valve is being used at the initial point of saturation, and if the anode curve lies well to the left of the grid zero ordinate, the variations of grid potential will be symmetrical; the asymmetry of the anode current curve is responsible for the rectification obtained. Now if we could make the negative half-oscillations stronger than the positive half-cycles we would get still stronger rectified currents. This is accomplished by the retroactive amplification obtained on a circuit of the Fig. 132 type, which causes the retroaction of the negative half-cycles to be greater than that of the positive ones. When rectification is obtained by means of grid current phenomena, the variations of grid potential are *not* symmetrical; the result of retroaction is then to accentuate this asymmetry on which the strength of the rectified signals depend.

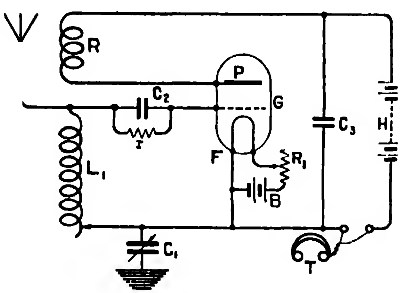


FIG. 133.—A practical circuit in which a valve acts simultaneously as a retroactive amplifier and as a detector.

This effect is usually overlooked when discussing circuits of this type, but it is one of considerable importance.

Simple Form of Retroactive Receiver.—Fig. 133 shows a very simple circuit which can be used for retroactive amplification. A grid condenser C_2 of about 0·0003 mfd., shunted by a resistance r of about 3 megohms, is used for obtaining rectification. No potentiometer is required. The filament current and anode voltage are variable and are adjusted to give the

loudest signals in the telephones T. If the filament-heating accumulator is of suitable voltage, the filament current rheostat may be omitted. The coupling between R and L_1 should be variable. In cases, however, where it is desirable to keep the coupling fixed, the valve may be made to pass through the pre-oscillatory stages by increasing the filament current until the loudest signals are heard.* The best method, however, is to vary the coupling between R and L_1. The retroactor coil R, which is aperiodic, should at first be loosely coupled to L_1. The aerial tuning inductance L_1 and the variable condenser C_1 are then tuned until the loudest signals are obtained. The anode battery H and the filament current regulator R_1 are then adjusted to give the maximum response in the 'phones T. Then tighten the coupling between R and L_1 gradually. Signals will become louder and louder, and will become a little harsher in tone. When the coupling is tightened still further the valve commences to oscillate of its own accord and a continuous rustling sound is heard in the 'phones. Signals will still be heard, but the distinctive notes of particular stations will be lost; all stations, no matter what their spark frequency may be, will give the same low, harsh note in the receiver. The explanation of this effect does not come within the scope of this chapter, but is given later. It may be that on tightening the coupling still further a continuous high musical note is produced which is due to the oscillatory circuit across grid and filament oscillating at two slightly different frequencies, which interfere with each other and produce a continuous "howl," the exact nature of which is discussed in the chapter on *beat* reception. This howling is often produced by setting the condenser C_1 at too low a value. It is stopped by setting C_1 at a higher value and loosening the coupling of R.

Tuned and Aperiodic Anode Oscillatory Circuits.—In Fig. 133 the anode circuit is aperiodic. This arrangement has the advantage of requiring less adjustment The aperiodic retroactor has a natural frequency which should be less than the frequency of the oscillations which will have to pass through R. If the circuit is to be used, say, for receiving waves from 200 to 1,000 metres, the coil R should not have a natural

* This is probably usually due to a slight steepening of the anode-current curve, which produces a greater amplifying effect. In certain cases it may be due to an alteration of the position of the operating point on the characteristic curve.

wave-length of more than 200 metres. This natural wave-length may easily be calculated.

Such aperiodic coils are not so suitable when the wave-length received differs considerably from the natural wave-length of the rectroactor coil. When it is desired to cover a considerable range of wave-lengths, it is preferable to use different values for the retroactor coil. It should, for example, be tapped off into sections, a larger number of turns being used when long wave-lengths are to be received.

Although aperiodic coils are undoubtedly very useful in anode circuits, less interference from other stations is usually experienced when the anode circuit is accurately tuned to the incoming wave-length. The amplification effect is also increased and may be of value when weak signals are being received.

It must be noticed, however, that if the anode circuit is made so that it can be tuned (*e.g.* by connecting a variable condenser across R), it must always be tuned, or very nearly tuned, to the same frequency as the incoming oscillations, otherwise the strength of signals obtained will be greatly decreased. A badly tuned anode circuit is infinitely worse than an aperiodic anode circuit.

Direct Magnetic Retroactive Coupling.—We have so far considered the use of a retroactor coil to obtain the special kind of amplification under consideration. There are, however, at least four methods altogether of obtaining retroaction. The four methods of coupling the plate circuit to the grid circuit are :—

(1) Indirect magnetic coupling.
(2) Direct magnetic coupling.
(3) Electrostatic coupling.
(4) Conductive coupling.

All retroactive circuits employ one or other of the above systems of coupling, although sometimes in a disguised form. There is not very much to choose from in the various circuits which have from time to time been devised. They mostly accomplish the same result, although in different ways.

We have already seen the ways in which retroact on may be obtained by indirect magnetic coupling ; a simple oscillation transformer is used. We can, however, as stated above, get much the same effect by the use of an auto-transformer

coupling, which is the simpler meaning of the expression "direct magnetic coupling."

Fig. 134 shows a circuit in which auto-transformer coupling is utilised to produce retroaction. The closed receiving circuit consists of a coil L_2, another inductance L_3, and a variable condenser C_2. This circuit is connected across the grid and filament of a valve, and produces radio-frequency currents in the anode circuit which consists of the anode P, battery H, 'phones T, inductance L_4, a part of the inductance L_3 from S to E, and the filament F. A sliding contact S moves along the coil L_3 and so regulates the amount of L_3 that is included in the anode

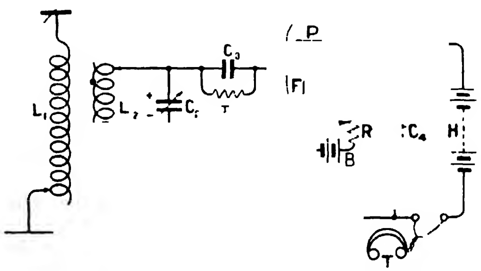


FIG. 134.—Circuit in which auto-coupling produces retroaction.

circuit. When S is at the bottom end of L_3 there is no retroaction, but when S is at a position such as that shown, the portion SE of L_3 is common to both anode and grid circuits, and, owing to the auto-transformer coupling, the oscillations in the anode circuit retroact on those in the grid circuit. The degree of retroaction will depend on the position of S. If we desire to tune the plate circuit more accurately we can tune the variable inductance L_4 in the anode circuit.

Theory of Auto-Coupled Retroaction.—The theory of the action of such a circuit as Fig. 134 is interesting, since it will help us to understand the principle of retroactive amplification, and also will prevent us from connecting up similar circuits which will not work when the time comes for the practical experiment.

If retroactive amplification is to be obtained, the energy communicated from the anode oscillatory circuit to the grid oscillatory circuit must result in a reinforcing of the

oscillations in each circuit. Since the oscillations in the anode and grid circuits are of the same frequency all that is necessary is to see that the oscillations "fed back" from the anode circuit to the grid circuit are in phase with the oscillations taking place in the grid oscillatory circuit. If the oscillations are induced back into the grid circuit in a reverse manner, any oscillations in the grid circuit would be neutralised by the reverse-phase oscillations communicated by the anode circuit. Looking at Fig. 134 we can consider two distinct oscillatory circuits, the grid circuit $L_2L_2C_2$ and the anode circuit L_4 and the portion SE of L_3. This anode circuit might be tuned if desired. It is a well-known fact that if two oscillatory circuits have a portion of an inductance in common, this portion in our case is SE. When the connections are as shown, a rising positive potential on a grid will produce an increasing current through the anode circuit. This current through SE will strengthen the existing current, which results in a rising positive potential on the grid. In Fig. 134, the coil L_4 could be omitted. We can now consider the circuit $L_2L_3C_2$ as the anode oscillatory circuit which is energised by currents passing through a portion of the inductance. The grid is connected to the point in this circuit which will produce retroaction.

Single Circuit Retroaction.—The previous section brings us to what one may conveniently call "single circuit" retroaction. That is to say, only one oscillatory circuit is provided. The commonest method—and, incidentally, the best—of obtaining regenerative action is to provide an anode circuit coil coupled to the grid circuit inductance. The advantage of this arrangement is that the coupling between the two coils may readily be varied between zero and maximum by rotating one of the coils or varying the distance between them. A very fine adjustment of retroaction is thus obtainable, and practice shows that variable "back-coupling" is a very important factor when reciving undamped wave (or "spark") signals.

One of the disadvantages of a retroactor coil is that the receiver requires two coils, while another is that a given anode circuit coil will only give good signals over a certain range of wave-lengths. The best conditions are those when the anode circuit coil has a natural wave-length approximating to but slightly less than that of the incoming signals. A retroactor coil, unless of high resistance, possesses a natural wave-length

as a result of its inductance and distributed capacity, and this wave-length should be just less than the lowest wave-length it is desired to receive. A receiving set will almost invariably require two ranges for the retroactor coil if a complete range of wave-lengths is to be covered. Matters may be somewhat improved by winding the retroactor coil with resistance wire.

These disadvantages are largely absent when only one oscillatory circuit is provided. This circuit may be directly or indirectly coupled to the aerial. The inductance is connected across grid and anode, while the filament connection is taken from a sliding contact on the inductance. By moving this contact the retroaction may be varied. Such a circuit is similar to Fig. 134 without L_1 and with S connected to the bottom of C_2. The filament connection slides along L_2 (L_3 being omitted).

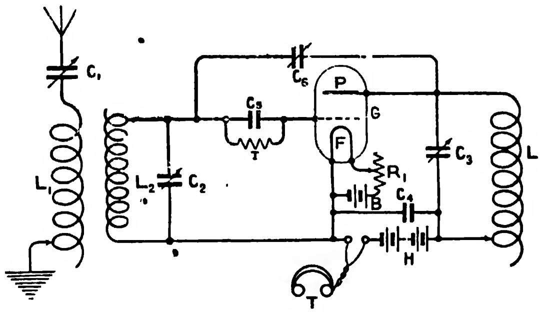


FIG. 135.—Circuit employing capacitative coupling to produce retroaction.

Electrostatic Retroaction.—The third method of obtaining retroaction is by using an electrostatic capacity coupling between anode and grid oscillatory circuits.

Fig. 135 shows a retroactive circuit which is simply an ordinary circuit containing grid and anode oscillatory circuits coupled by means of a variable condenser C_6, which has a capacity of about 0·0001 mfd. There is no actual magnetic coupling between L_3 and L_2, but retroaction is obtained by means of the condenser C_6. By increasing the capacity of C_6 the retroaction increases until a point is reached when the valve oscillates of its own accord. The condenser C_6 has the effect of increasing the capacity effect between the actual anode P and the grid G. The capacity of the grid in a French, R, or Ediswan type ES4 valve, is about 0·000015 mfd.

Conditions for Electrostatic Retroaction.—The degree of

retroaction will depend not only on the capacity of C_6, but also on the self-inductance of the coil L_3. The amplification obtained will depend on the product $L_3 \times C_6$. This product should be less than the product $L_2 \times C_6$. The capacity C_6 and the inductance L_3 should be variable. When $L_3 \times C_6$ is small, the retroactive amplification is greatest when $L_3 \times C_6$ is just below a certain critical value. When $L_3 \times C_6$ is above this value the vacuum tube commences to oscillate of its own accord.

When $L_2 \times C_2$ is small and the self-inductance of L_3 is large, retroactive amplification may take place owing to the coupling effected by the small condenser formed by the anode and the grid. Conditions may even be such that sustained oscillations are set up in the circuit.

Armstrong's Circuits.—This peculiar fact was noticed and explained by E. H. Armstrong,* in 1913. He found that when using the vacuum tube as a detector considerably better results were obtained when the anode circuit was tuned. He used a circuit somewhat similar to that of Fig. 136. In the

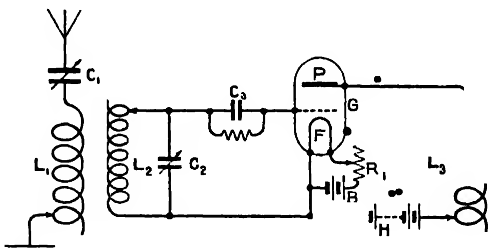


FIG. 136.—Showing the use of an inductance in the anode circuit of a valve.

anode circuit he included a variable inductance L_3, which was found to give stronger signals. The explanation lies in the fact that the self-inductance of L_3 acts in a "regenerative" (as he termed it) manner on the grid circuit through the electrostatic coupling existing within the tube itself.

As has been explained, if this coupling is not sufficient, it may be varied by connecting a small condenser across the anode and grid.

Fig. 137 shows another Armstrong patent (British

* British Patent 147042 (Oct. 29, 13). *Proceedings Inst. Radio. Eng.*, Sept. 1915. Armstrong has been allowed in the American Patent Office the date Jan. 1913 as that on which he invented "regeneration."

Patent 24231/13 (Dec. 18/13). The telephone receivers are shown at R and are shunted by a variable condenser C_2. The receiving circuit SCL is connected to the grid G by a condenser C_1, and to the filament F by a condenser C_2 and the telephones (or other suitable inductance) R. The

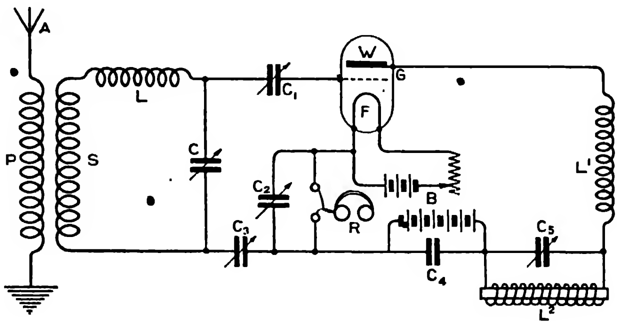


FIG. 137.—One of Armstrong's circuits.

anode circuit includes the inductance L_1, condensers C_4, C_5 and also the condenser C_2 and inductance R. A battery B and impedance L_2 are arranged as shown. The impedance L_2, which may be a pair of 'phones, does not produce the radio-frequency coupling which is effected by the self-inductance of L_1, and especially by means of the capacity C_2, which is common to both grid and anode circuits.

Another form of Armstrong's circuit is shown in Fig. 138.

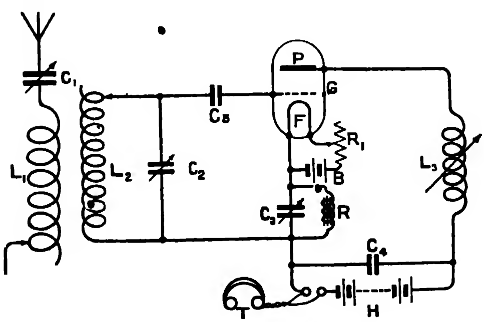


FIG. 138.—Another form of circuit claimed by Armstrong.

Here the anode oscillatory circuit may be tuned by means of the inductance L_3. The coupling between anode and grid circuits is effected by means of the variable condenser C_3.

which is shunted by an iron core inductance, such as a pair of telephone receivers. The action of this inductance is, according to Armstrong, a form of electromagnetic coupling. It seems, however, that this is not altogether the case, but that the purpose of the high self-inductance is simply (as in many other vacuum tube connections) to provide a path for the direct battery current from the filament to the anode without short-circuiting the capacity C_3, which effects the retroactive coupling. L. A. Hazeltine explains this,* and states that the use of a high non-inductive resistance will answer the same purpose, though requiring a higher anode battery voltage to give the same normal anode current.

The telephones T are connected as shown. The condenser C_4 is a by-path for the high-frequency currents in the anode circuit.

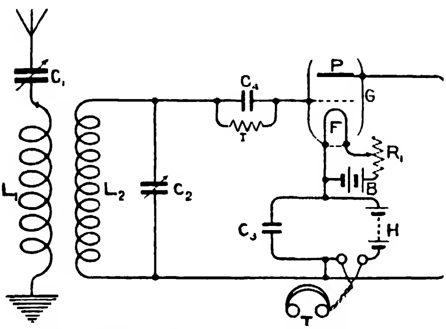


FIG. 139.—Another circuit claimed by Armstrong.

Fig. 139 shows another form of circuit discussed by Armstrong,† in which there is no tuned anode circuit. The retroactive coupling is effected by means of C_3.

The Circuits of Lee de Forest.—Lee de Forest has been responsible for a number of vacuum tube circuits of great value. Most of these have the receiving circuit connected across the anode and grid instead of across the grid and filament.‡ Fig. 98 was a typical set of connections.

A somewhat similar circuit is shown in Fig. 140, which illustrates the use of an electrostatic coupling condenser C_3, which causes the circuit to act more efficiently as a receiving instrument. To prevent the grid acquiring too strong a negative potential, as may happen when hard valves are used, a resistance R of one or two megohms may be connected from the grid to the filament.

If the condenser C_3 be adjusted to a certain critical value

* *Proc. I.R.E.*, **6**, 2, 88 (April, 1918).
† *Proc. I.R.E.*, **4**, 3, 265 (June, 1916).
‡ See British Patent 3950/15 (March 12/14).

sustained oscillations may take place in the circuit L_2 C_2. For the reception of spark signals its value should be just less than this.*

A modified arrangement which may be used consists in

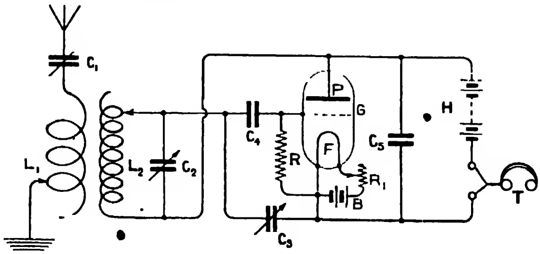


FIG. 140.—De Forest circuit in which retroaction is obtained by means of condenser C_3.

placing the condenser C_3 directly across grid and filament and eliminating the leak R. Such a circuit gives very good results and may be used for spark or continuous wave reception. It appears to work satisfactorily without a special grid leak.

Fig. 140 is a modification of Lee de Forest's circuits, and is sometimes known as an "ultraudion" circuit.

Special Form of Capacitative Coupling.†—Fig. 141 shows a circuit in which retroactive amplification is obtained in rather a peculiar manner. A semicircular metal plate P_2 is connected by a flexible wire to the anode P_1 of the vacuum tube. By placing the semicircular plate over a portion of the inductance coil L_2 retroactive amplification is obtained. The effect appears to be similar to that obtained when a condenser is connected across the anode and grid of a vacuum tube. In

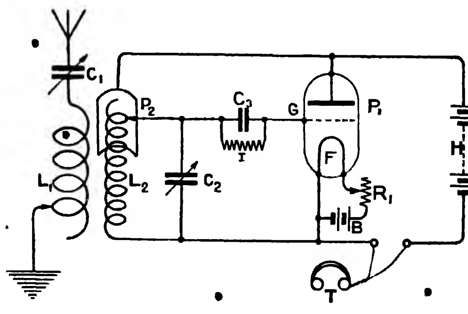


FIG. 141.—Retroactive amplification obtained by placing a semicircular plate P_1 over the inductance coil L_2.

* De Forest claims that with similar circuits he was the first to make a vacuum tube oscillate.

† Apparently due to E. E. Bucher. See also *Wireless Age*, July, 1919.

this case, the capacity of the turns of L_2 acts as one side of the condenser while the other side consists of the plate P_2.

Retroaction may be obtained in several ways. The plate P_2 may, for example, be placed on the inductance L_1. Another arrangement is to connect the plate P_2 to the variable contact on L_2 instead of to P_1. An inductance is now provided in the anode circuit of the vacuum tube and the semi-circular plate is placed on this coil.

The degree of retroaction may be varied by altering the number of turns which come under the influence of P_2. The value will vary with the wave-length. The capacity between P_2 and the inductance coil will require to be greater for short waves than for long waves.

Retroaction by means of Resistance Couplings.—We have now considered how retroaction has been obtained by means of direct and indirect magnetic coupling, and by electrostatic coupling. We now come to what may be called "conductive" or "resistance" coupling.

In Fig. 142 is a circuit in which the retroaction is obtained

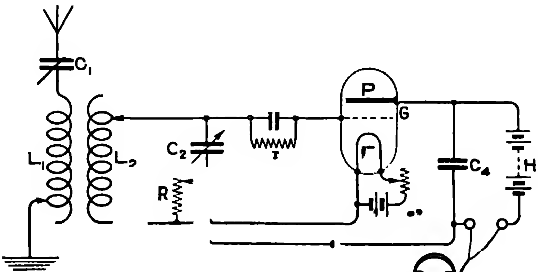


FIG. 142.—Retroactive amplification obtained by means of resistance coupling.

by the resistance R, which is non-inductive and of a rather low value. It has the disadvantage of tending to damp the oscillations in the grid oscillatory circuit, but it illustrates the use of resistance retroaction. The resistance R is shown with a variable tapping or slider.

If a resistance be included in the anode circuit of a valve and one side of the input circuit is connected to a point on this resistance (the other side being connected to the grid) the retroaction obtained will produce absorption.* If,

* Sometimes termed "reverse retroaction" because the reverse of amplification takes place.

however, two valves are used,* coupled by resistance, suitable retroaction is obtained and is exceedingly valuable, especially when steady potentials are to be magnified. This principle of resistance retroaction is used in W. H. Eccles' trigger relay and L. B. Turner's "kallirotron." These important devices are described later.

Weagant's Retroactive Circuits.—Roy A. Weagant favours the circuit shown in Fig. 143, which may be used successfully for the reception of damped waves. Across the anode circuit of a vacuum which is being used in the ordinary way as a detector, is connected an oscillatory circuit L_3C_3, which may be tuned. This circuit has been called the "X" or *tertiary* circuit, and it acts in a retroactive way similar to

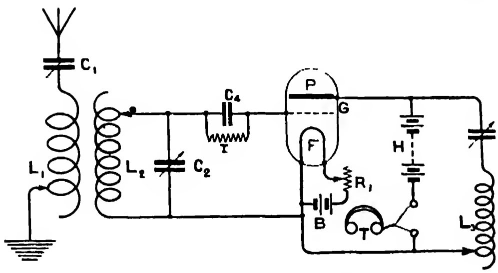


FIG. 143.—Weagant receiving circuit.

that of Armstrong's tuned anode circuit. This anode oscillatory circuit may be coupled to a greater or less degree to the steady current anode circuit by adjusting the condenser C_3. It is to be noted that only oscillatory current flows in the circuit L_3C_3, the steady anode current, varied at audio-frequency, passes *via* the anode battery H and the telephones T. Other inventors have also used this circuit.

Combination Retroactive Circuits.—Two or more methods of obtaining retroaction frequently act together or in opposition. The most usual arrangement, and the most convenient one, is to have an anode oscillatory circuit retroacting on the grid oscillatory circuit by means of a radio-frequency transformer. In this case there is always a certain amount of electrostatic retroaction due to the capacity of the electrodes in the vacuum tube. This at times, in certain types of tube, may cause continuous self-oscillation, even when the anode oscillatory

* The present author has produced resistance retroaction in a single valve of special type termed a "negatron."

circuit is right away from the grid circuit. This is a great disadvantage if we desire retroactive amplification. We can, however, prevent the tube from oscillating by causing retroaction which will oppose that due to electrostatic influences. This may be accomplished by reversing the retroactor coil so as to tend to damp out oscillations in the other circuit.

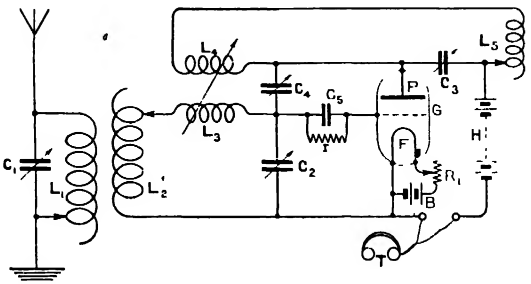


FIG. 144.—Long-wave receiving circuit employing inductive and capacitative coupling.

Even this is not always effective, especially when the self-inductance of the grid and anode circuit inductances are large. Oscillations may even be set up when the retroactor is reversed and tightly coupled. To avoid this a resistance may be included in the grid oscillating circuit.

Frequently, however, the opposite effect is desired. The

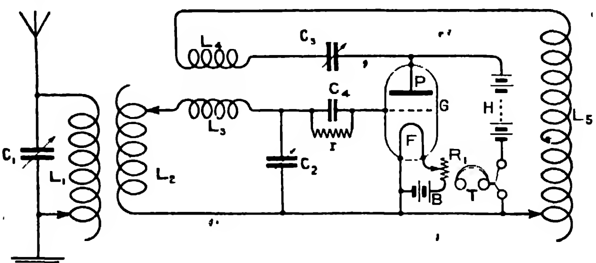


FIG. 145 —Modified Weagant circuit.

retroactive effect may not be sufficiently strong, in which case it can be increased by connecting a variable condenser across the grid and anode of the vacuum tube. This is shown in Fig. 144. Additional retroaction is obtained by means of C_4. It may be used in cases where only small wave-lengths are in use and the grid and anode inductances are of small dimensions ;

or where the coupling coils are small and their mutual inductance consequently insufficient to provide sufficient retroaction.

A Modified Weagant Circuit.—Fig. 145 is a Weagant circuit in which retroaction is obtained partly by coupling the anode and grid oscillatory circuits by means of a radio-frequency

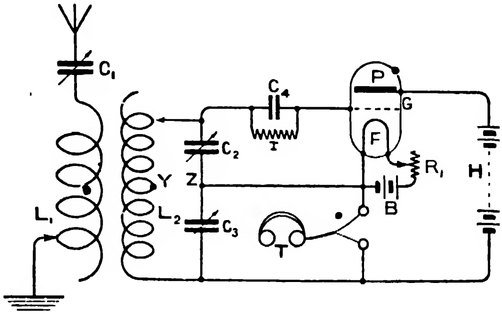


FIG. 146.—Another retroactive circuit.

transformer L_3L_4. The coils L_4 and L_3 may be fixed inductances forming part of the anode and grid oscillatory circuits respectively.

Another Retroactive Circuit.—A circuit similar to that of Fig. 146 has been discussed by E. H. Armstrong.* The connections will be seen from the figure. He contends there will always be a point Y on the inductance L_2 which has the same instantaneous potential as the point Z. If the capacity of C_2 equals that of C_3 the point will be about half-way along the used portion of L_2. For a given adjustment, we might then connect the points Y and Z by a wire without altering the action of the circuit. This wire would, however, make the special position of the telephones unnecessary, since

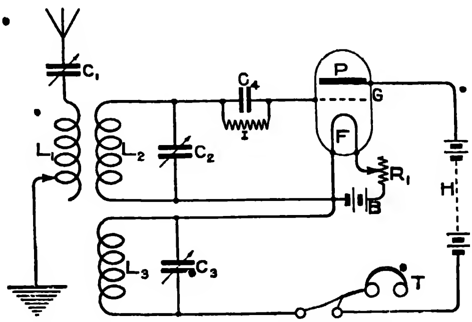


FIG. 147.—Fig. 146 circuit redrawn.

* *Proc. I.R.E.*, 3, 2, 156 (April, 1917). See also British Patent 107001 (May 23/16) of L. de Forest.

it would provide a path for the steady anode current to flow from anode to filament. The circuit could therefore be redrawn as in Fig. 147, which is an ordinary retroactive circuit. Such an argument is hardly correct, because in Fig. 146 there is not necessarily any electromagnetic coupling between the upper and lower parts of L_2.

Some Typical Retroactive Circuits.—In Fig. 148 is a collection of retroactive circuits frequently used for the reception of undamped waves. Fig. 148 (*a*) shows a loose-coupled arrangement in which the retroactor is aperiodic. Fig. 148 (*b*) shows an auto-coupled circuit in which the retroactor is

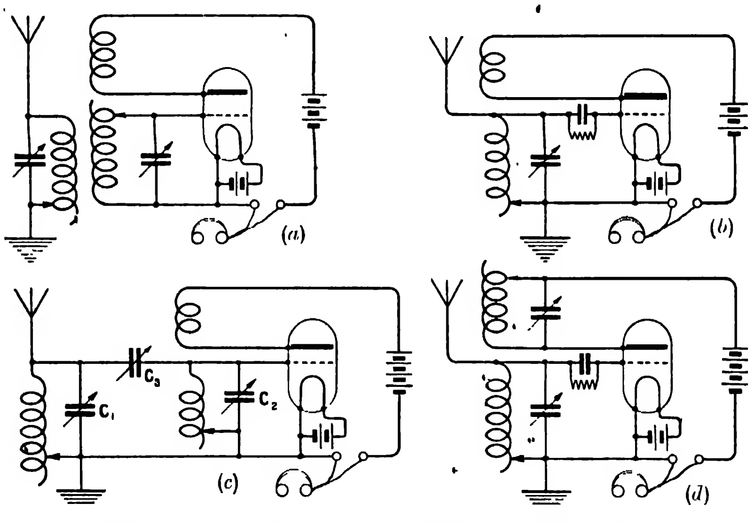
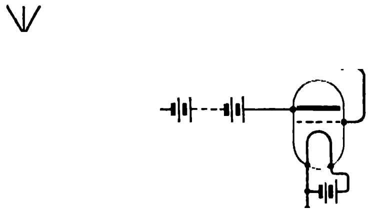


FIG. 148 (*a*), (*b*), (*c*), (*d*).—Various retroactive receiving circuits.

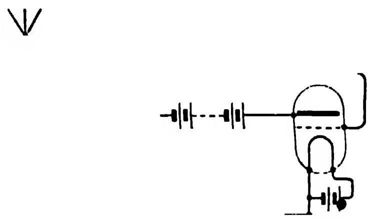
aperiodic. Fig. 148 (*c*) is a similar circuit in which the aerial circuit is coupled to the grid oscillatory circuit by means of a condenser C_3. Retroaction is obtained by means of an aperiodic retroactor coil.

Fig. 148 (*d*) is a typical circuit in which both grid and anode oscillatory circuits are tuned. Fig. 148 (*e*) is a circuit not previously described but which presents no specially new features. The aerial circuit forms part of the anode oscillatory circuit and not the grid circuit as is more usual. The grid oscillatory circuit R is now made aperiodic, and is coupled to the anode circuit. Oscillations in the aerial circuit induce

oscillations in the retroactor, which cause high-frequency variations of the grid potential. Magnified oscillations are set up in the anode circuit which assist the incoming oscillations. It should be noted that the high potential end of the retroactor should be connected to the grid of the valve. The obvious development of this circuit is that in Fig. 148 (f), which now shows the grid oscillatory circuit tuned. The circuit of Fig. 148 (g) shows the grid and anode oscillatory circuits coupled by means of the condenser C_3, the actual inductances being apart. Fig. 148 (h) is similar to Fig. 148 (g), except that the inductances are now coupled together

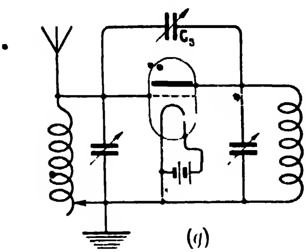


(e)

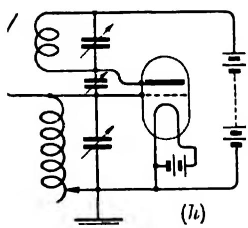


(f)

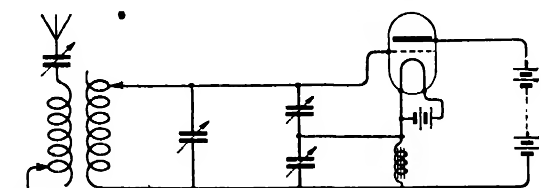
FIG. 148 (e), (f).—Retroactive circuits. No means of detection is shown.



(g)



(h)



(j)

FIG. 148 (g), (h), (j).—Further retroactive circuits. No means of detection is shown.

magnetically. The circuit of Fig. 148 (j) has already been explained.

All the above circuits may be used in a variety of ways. They may be made to rectify as well as amplify, in which case a leaky grid condenser may be connected in the grid circuit and telephones in the anode circuit; any of the other methods of obtaining rectification may be employed; in this volume, however, the author proposes in nearly all cases to show a leaky grid condenser whenever he wants to indicate that the vacuum tube in question is meant to function as a detector. A small grid cell will usually be shown when the tube is merely acting as an amplifier.

When the vacuum tube of Fig. 148 is meant to rectify, a pair of high-resistance 'phones (or a telephone transformer) shunted by a condenser, is included somewhere in the anode circuit, preferably near to the filament.

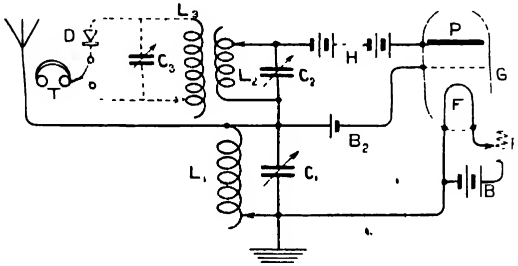


FIG. 149.—Highly selective retroactive circuit.

If the valve is merely to be used as a retroactive amplifier, the detector circuit (such as a crystal and pair of 'phones, or another valve acting as detector) may be connected across one of the oscillatory circuits in which amplified oscillations are taking place.

Two Selective Retroactive Circuits.—A form of connections which has been described by L. A. Hazeltine,* in a paper before the Institute of Radio Engineers, is given in Fig. 149. Retroaction is effected by means of the magnetic coupling between the inductances L_2 and L_1. The anode oscillatory circuit L_2C_2 is connected *across anode and grid*, and not across anode and filament which is the more usual position.

These connections are interesting since they are very

* L. A. Hazeltine, *Proc. I.R.E.*, 6, 2, 91, April, 1918. See also J. Scott-Taggart, "Some Modern Vacuum Tube Circuits," *Wireless Age*, Oct., 1919.

selective. Both grid and oscillatory circuits are tuned to the incoming waves and the retroactive amplification will be confined to that wave-length. The waves from stations using slightly different wave-lengths on either side will not only be not amplified, but will be absorbed. The valve "will therefore have a strong tendency to reduce interference, since it absorbs energy from oscillations at other frequencies than that to which it is tuned. The vacuum tube used in this way for combined retroactive and absorbing action should not also be used as a detector; for its grid is connected (or closely coupled) to the antenna circuit L_1C_1. A second vacuum tube (or other detector) should be connected in the usual way to the circuit L_2C_2, where interference may be further minimised in the usual manner by the loose coupling of the two tuned circuits."

In the circuit of Fig. 149 the detector circuit L_3C_3DT is loosely coupled to the circuit L_2C_2, and is shown in dotted lines. A second valve used as a detector may be substituted for D and T, as we will see in the next chapter.

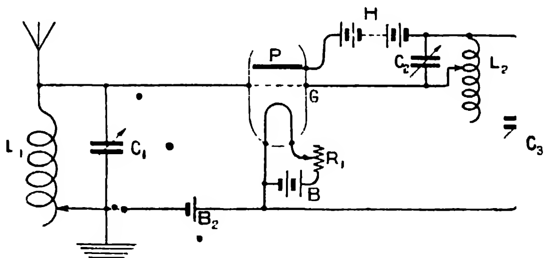


FIG. 150.—Highly selective circuit in which retroaction is obtained by means of the condenser C_3. The detector circuit is coupled to the inductance L_2.

Fig. 150 is an example of a similar circuit in which, however, the mutual effect between grid and anode oscillatory circuits is obtained electrostatically by means of a condenser C_3. The detector circuit is connected or coupled to the circuit L_2C_2.

Remarks on Two Popular Circuits.—The type of receiving circuit shown in Fig. 148 (*a*) is very useful, but has the disadvantage * of "incrementing," or amplifying by retroaction, not only the waves we desire to receive, but also the waves of

* *Loc. cit.*, page 83.

interfering stations which have forced themselves on to the receiving circuit, even though the latter is not tuned to them. The amplification of this type of arrangement, using an aperiodic anode oscillatory circuit, is constant for all frequencies received, and trouble is likely to be experienced through jamming and "atmospherics."

The circuit of Fig. 148 (*d*), which has both grid and anode *oscillatory circuits tuned, absorbs waves longer than a certain* critical value, but will amplify equally well all waves less than this value. It has, therefore, distinctly selective qualities. If the retroactor coil is reversed, and the effect of this does not completely destroy the retroaction produced by the self inductance of the coils and the electrostatic coupling inside the valve, the circuit will amplify waves longer than a certain value, but will absorb the shorter waves. It is not, however, capable of doing what Fig. 149 does; namely, amplify the required waves and damp out the unwanted waves of lengths on either side.

Recommended Simple Retroactive Circuit.—Fig. 151 shows a simple retroactive amplifier receiving circuit suitable for

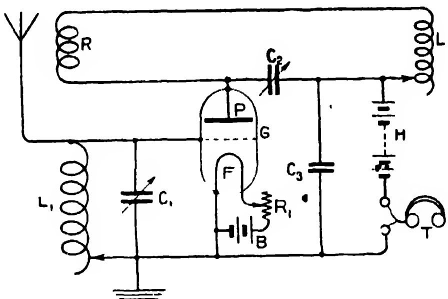


FIG. 151.—Recommended circuit employing retroactive amplification especially suitable for the reception of long waves.

any wave-length. The anode oscillatory circuit is composed of a retroactor coil R in series with a variable inductance L_2, the whole being shunted by a variable condenser C_2 of about 0·001 mfd. capacity. To vary the coupling between L_1 and R, the latter coil may be rotated on its axis. This circuit acts as a detector as well as a retroactive amplifier; the grid is connected *via* L_1 to the negative end of the filament, and grid current detector action is utilised. A leaky grid

condenser might be used if desired. The shunting condenser C_3 across 'phones and anode battery is not altogether necessary, the capacity of the telephone leads being frequently sufficient to pass the high-frequency currents. It is, however, preferable to use the condenser. If the condenser C_3 is made variable the various stages prior to self-oscillation can generally be obtained by adjusting the condenser.

When "listening-in," the anode oscillatory circuit may be cut out by shorting C_2. The circuit L_1C_1 may then be tuned until the loudest signals are heard in the 'phones T. The anode oscillatory circuit may then be unshorted and, with the coupling of R fairly loose, tuned until signals reach their optimum strength. The coupling of R is then tightened until

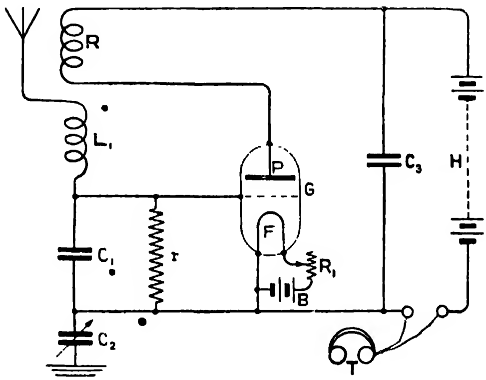


FIG. 152.—Circuit especially suitable for the reception of very short waves.

the signals, which will be gradually getting louder, have reached their optimum, or most effective, value. If the coupling of R is tightened still further, a rushing sound will be heard in the 'phones, indicating that the valve is oscillating of its own accord.

The variation of the coupling will cause a small variation in the tuning of the circuits which may be compensated for by a slight readjustment of C_1 and C_2. Condenser C_2 may usually be omitted without affecting signal strength.

Retroactive Circuit for very Short Waves.—A retroactive circuit which is especially useful for very short waves, or in cases where the aerial tuning inductance is of small dimensions, is given in Fig. 152. The circuit L_1 is of such small dimensions

that to connect the grid and filament of the valve across it would result in inefficiency. Connection is therefore taken to the plates of a condenser C_1 in series with the aerial circuit. The oscillating potentials across this condenser are applied to the grid of the valve and set up magnified oscillations in the aperiodic anode oscillatory circuit R. which retroacts on the inductance L_1. The condenser C_1 may have a capacity of 0·0003 mfd., and when shunted by the resistance r of two or three megohms, also acts as a leaky grid condenser to produce rectification. The condenser C_2 is used for tuning purposes, and also assists the circuit to retroact more readily. A circuit somewhat similar to this was evolved by L. B. Turner at Signals Experimental Establishment of the British Army for use on sets working on wave-lengths less than 100 metres.*

Combined Audio and Radio-frequency Retroaction.—We saw in the double magnification circuit of Fig. 129 how the rectified current from the detector may be led into the grid circuit and

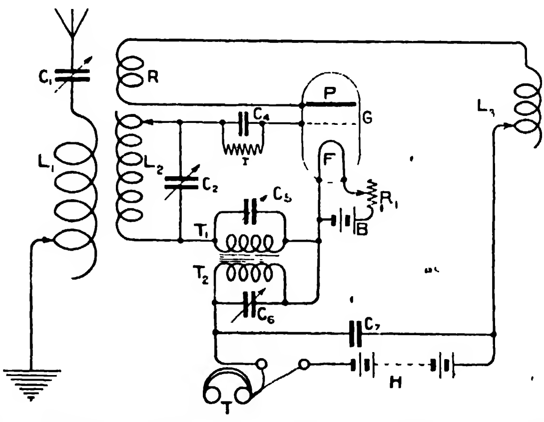


FIG. 153.—Circuit employing both audio and radio-frequency retroaction.

be amplified by the valve. E. H. Armstrong has used the vacuum tube as a retroactive device not only for the radio-frequency currents involved, but also for the low-frequency pulses which take place in the anode circuit of the valve when the latter is used as a detector. Fig. 153 is a modified circuit in which radio-frequency retroaction is obtained through the coupling between R and L_2, and audio-frequency coupling by means of the transformer T_2T_1. The audio-frequency pulses

* See also J. Scott-Taggart, *Wireless World*, Nov. 27, 1920.

in the anode circuit pass through the winding T_2 of the transformer and so retroact on the winding T_1 which forms part of the grid circuit. Condensers C_5 and C_6 allow the passage of the high-frequency component of the anode current, and may, if variable, be used to resonate the windings of the transformer to the audio-frequency pulses. This circuit is of theoretical interest, but is difficult to design and operate.

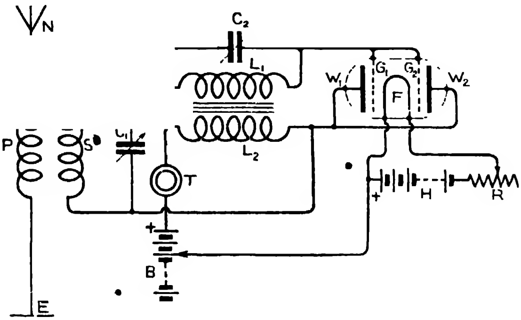


FIG. 154.—A circuit employing LF retroaction.

Lee de Forest and C. V. Logwood, in British Patent 3950/15 (March 12/14), describe the arrangement of Fig. 154, which also appears to give retroactive amplification of radio- and audio-frequency currents. The receiving circuit is connected across grid and anode.

It is doubtful whether the complications resulting from the use of such circuits warrant their use.

CHAPTER VI.

MULTI-STAGE HIGH-FREQUENCY AMPLIFIERS.*

Need for Further Amplification.—We have already pointed out that the rectified current obtained with a vacuum tube detector is proportional to the square of the amplitude of the received oscillations. If, say, we halve this amplitude we will only get *one quarter* of the rectified current, and so only quarter the strength of signals. If incoming oscillations are very weak it will be clear that practically nothing will be heard in the receivers. If we picture for a moment the grid current curves and anode current curves obtained with an average vacuum tube, we will recall that the "bends" are not very sharp. If the variation of grid potential is only very small, the portion of the grid curve (or anode curve) traversed by the representative point is only very small and is practically straight. As the voltages impressed on the grid become larger, the disproportion between increases and decreases of anode current becomes more accentuated and the resultant strength of signals rapidly increases.

It is, therefore, greatly to our advantage to amplify our weak signals until they attain an amplitude sufficient to operate effectively the detector in use.

High-frequency Amplification.—The problem before us is to arrange a circuit in which the incoming oscillations are first amplified and then detected. We have seen how Armstrong, Franklin, and others have used a retroactive coupling to increase the duration of the wave-trains of damped waves. The theoretical limit of this form of amplification is, however, reached when the incoming group of oscillations is made to die out just before the next group comes along. If the amplification is carried beyond this point, the vacuum tube commences to oscillate of its own accord and entirely new conditions are brought into force.

* See also J. Scott-Taggart, *Wireless World*, Nov. 1919, *et seq.*

The early single-valve circuits of Marconi's Wireless Telegraph Company and the circuits of Arco and Meissner and others, used the valve solely as an amplifier of high-frequency oscillations, which were usually subsequently rectified by means of a crystal detector. Sometimes the detector circuit was connected across the anode oscillatory circuit, as in Figs. 114 and 115; at other times it was connected across an oscillatory circuit loosely coupled to the anode oscillatory circuit; an example of this is given in Fig. 116, and by its means more selective tuning was possible.

A crystal detector, however, is never too reliable and the use of a valve as a detector is now universally preferred.

Methods of Coupling.—The various methods of coupling a detector circuit, or the input circuit of a second amplifying valve, to the anode circuit of the first valve are given below.

(1) Direct magnetic coupling.
(2) Indirect magnetic coupling.
(3) Use of resistance coupling.
(4) Use of choke-coils.
(5) Use of iron-core transformers.
(6) Electrostatic coupling.

Auto-transformer Couplings between Valves.—Perhaps the simplest method of using two vacuum tubes in a receiving

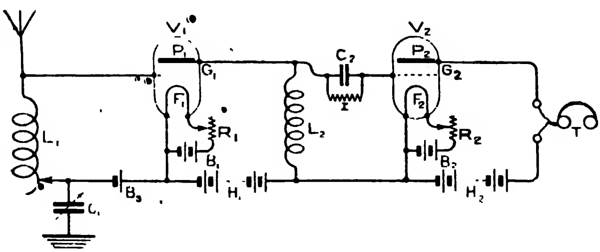


FIG. 155.—A two-valve receiver using an aperiodic auto-coupling arrangement between two valves.

circuit is that shown in Fig. 155. Incoming oscillations passing through L_1 vary the grid potential and cause magnified oscillations to flow through the coil L_2, which may be aperiodic. The oscillations in L_2 will, in that case, be forced. If now we connect the grid and filament of a valve, arranged as a detector, across the inductance L_2, loud signals will be heard in the telephones T.

Use of Single Batteries.—It will be seen that we have used two anode batteries and two filament-heating accumulators. Now, these batteries are expensive, perhaps cumbersome, and always necessitate an abundance of connections. This can be avoided by using one anode battery and one filament accumulator and altering a few connections. The new arrangement, which is really identical in principle with Fig. 155, is that shown in Fig. 156. The filaments of the valves are connected in parallel and are heated by what is, usually, a four- or preferably a six-volt accumulator (B). Since the first tube acts simply as an amplifier and the second one acts under special conditions, the filament current for each is adjusted by a series resistance having a maximum value of

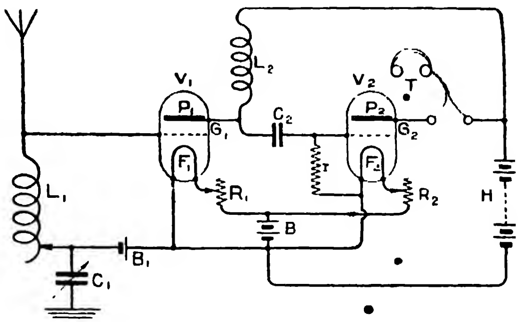


FIG. 156.—Two-stage receiver using single filament and anode batteries.

about 5 to 10 ohms. The anode voltage remains the same for both valves, but since that of the rectifying valve usually requires to be less than that for an amplifying valve, an arrangement similar to the one shown in Fig. 158 may be used; different voltages are tapped off the same battery.

It may be asked why the leak resistance r, which is of 1 or 2 megohms, is connected directly across the grid and filament instead of across the condenser C_2, as was done in Fig. 155. The reason is that if the resistance were across C_2, the anode battery H would act through it and give the grid of the second valve a positive potential. As things are, the condenser plates are well insulated from each other and only *pulsating* or oscillatory variations are transmitted to the grid through C_2. Some means, however, must be provided for restoring the grid potential to its normal value after each

group of waves. The grid leak is therefore connected directly to the filament, as shown.

Use of Three Vacuum Tubes.—There is nothing to prevent the principle of Fig. 155 being extended. We could use the second valve to amplify the oscillations still further and then use a third valve as a detector. This arrangement is carried out in Fig. 157 and is in every way practicable. The anode circuit of the first valve is $P_1L_2H_1F_1$; oscillating potentials across the coil L_2 affect the grid G_2 of the second valve in the anode circuit $P_2L_3H_2F_2$ of which still further amplified oscillations take place. These oscillations are now made to affect the grid potential of the third valve which is arranged to act as a detector. They are here rectified and affect the telephones T.

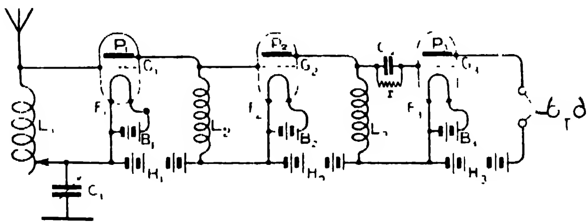


FIG. 157.—Three stage amplifier employing aperiodic coils to couple the vacuum tubes

The inductances L_2 and L_3 are aperiodic and will respond effectively to a fairly wide range of wave-lengths, as for example from 600 to 2,000 metres. To ensure their aperiodicity, the turns should preferably be spaced rather more widely than usual, to avoid self-capacity. The coils may be wound with very fine wire or with resistance wire to ensure them being aperiodic.

It might be asked what effect the steady anode voltage of one valve has on the normal grid potential of the second one. Practically none. True, there is a steady potential drop across L_2, but the resistance of L_2 is exceedingly small compared to the resistance of the valve between filament and anode. Thus if the resistance of the valve is 50,000 ohms and L_2 has a resistance of about 5 ohms, the normal grid potential of the second valve will be only $-0{\cdot}001$ volt, a negligible quantity. If the resistance of L_2 alone were about 500 ohms, the effect on the grid potential of the second valve would be noticeable. Since the electron current is flowing externally from anode to

filament through L_2, the top end of this inductance will have a negative potential with respect to the bottom end. This would give the grid G_2 a small negative potential which would be rather an advantage.

The disadvantage of the Fig. 157 arrangement is that a multiplicity of anode batteries and filament-heating accumulators are required. This disadvantage can be overcome by using the arrangement of Fig. 158. This circuit is of the same nature as Fig. 156. except that the second valve is *meant* to act as an amplifier and the third valve as a detector. The condenser C_2 is intended to insulate the grid from the steady voltage of the anode battery H, which would otherwise give

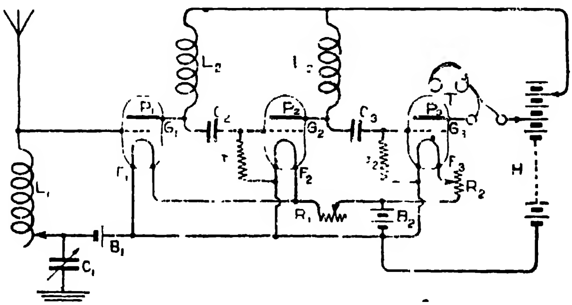


FIG. 158—A practical three-stage amplifier.

the grid of the second valve a potential equal to that of the anode of the first valve, whereas we require the second grid to have a potential in the neighbourhood of zero volts. The leak r_1 is of about 3 megohms and prevents the grid becoming too negative. When signals are being received, oscillating potentials are set up across the anode circuit $P_1L_2HF_1$ of the first valve and are communicated to the grid of the second valve through the condenser C_2. The resulting oscillating potentials on the grid of the second valve cause magnified oscillations to flow in its anode circuit $P_2L_3HF_2$. Oscillating potentials are then communicated to the grid of the third valve through C_3. This third valve is to act as a detector, and a separate filament current rheostat R_2 is provided, whereas the other two valves have one rheostat R_1 common to both since their functions are intended to be alike. Actually, there is no doubt that the second valve *does* act to a certain extent as a detector. This effect is non-existent in the method described

in connection with Fig. 161. A special feature of the Fig. 158 circuit is the method shown whereby the anode voltage of the first two amplifying valves is variable by the top plug, while the anode voltage of the rectifying valve is variable by means of another plug which will usually be lower down H than the first. This arrangement is not essential, but it will give the reader an idea of how the different valves of a multi-valve amplifier may be made to function under different conditions.

The Grid Potentials of the Different Valves.—It is interesting to note the grid potentials of the individual valves of such circuits. They are not, say, negative all at the same time. As a matter of fact, they are alternately positive and negative. Let us suppose the grid of the first valve to be suddenly made positive. An extra flow of electrons will pass from P_1 through L_2 and H to the filament. The bottom end of L_2 will therefore be negative, and consequently the grid of the second valve will be negative. This will cause the anode current through L_3 to decrease; the resistance of the anode circuit has increased and the potential of the anode has correspondingly increased. A positive potential is therefore impressed on the grid of the third valve. The sign of the grid potentials of the series of valves changes each time. If the amplifying arrangement has an odd number of valves the grid potential of the end valve will be of the same sign as that of the first valve. If, on the other hand, the number of valves used is, say, 2, 4, or 8, the grid potential of the last valve will be of opposite sign to that of the first. In the example taken, the anode current of each valve may either be increasing or decreasing. The telephones T are therefore not included in the part of the anode circuit common to all the valves, but only in the anode circuit of the end valve.*

Use of Tuned Anode Circuits.—The circuits from Fig. 155 to Fig. 158 may be made more selective and rather more sensitive by tuning the various anode oscillatory circuits while still utilising auto-transformer connections. All that is required is to connect variable condensers across the inductances L_2, L_3, etc. The fundamental circuit is given in Fig. 159. The anode oscillatory circuit L_2C_2 is now tuned to the incoming wave-length and no attempt is made to make L_2 aperiodic. Since the anode circuit is tuned there will probably be a certain

* This explanation is not strictly true in all cases owing to small phase changes.

amount of retroaction between it and the original circuit, but this is an advantage provided it is not sufficient to cause the first valve to generate oscillations of its own accord.

Fig. 160 is the type for those circuits using only one filament-heating accumulator and one anode battery. Circuits using any number of valves may be constructed on the same

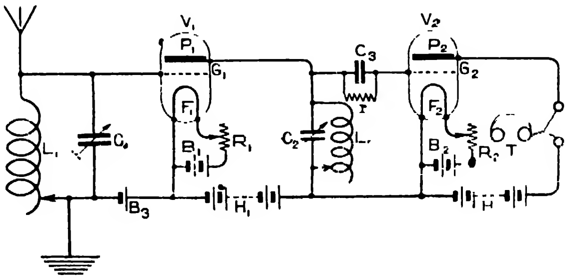


FIG. 159.—Two-valve receiver with tuned intermediary circuit.

principle. The inductance L_2 is shown variable in this circuit. The value of C_2 should be kept as small as possible.

Special Auto-transformer Coupling.—Still further selectivity is obtainable by using two sliding contacts on the variable inductances in the anode circuits. An arrangement is shown

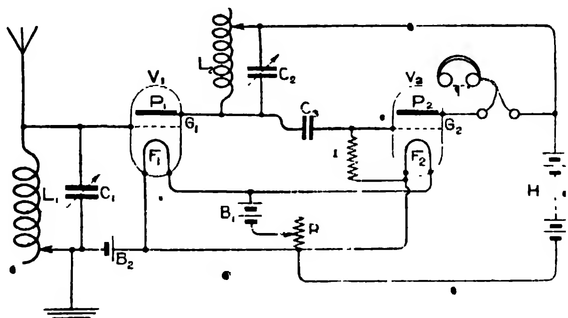


FIG. 160.—Practical two-valve receiver with an intermediary tuned circuit

in Fig. 161 which illustrates the use of four vacuum tubes in this manner. The anode circuit of the first tube includes the portion from S_1 to E of the inductance, while the grid oscillatory circuit is composed of the portion S_2 to E shunted by the condenser C_2. While the use of four valves is quite in order, the use of two variable tappings on the inter-valve inductance cannot be considered to be of sufficient value to

warrant its adoption in multi-valve amplifiers. The circuits employing indirect coupling are to be preferred.

Method of applying Varying Potentials to Grids of Auto-coupled Amplifiers.—In Fig. 161 is shown an interesting method of applying potentials to the grids of vacuum tubes in auto-coupled cascade amplifiers. A grid battery B_2 is provided, so as to give the grids G_1, G_2, and G_3 of the amplifying valves a suitable negative potential; the voltage of B_2 acts through L_1 in the case of G_1 and through the resistances r_1 and r_2 in the case of the second and third vacuum tubes. Since the internal resistance of the vacuum tube between grid and filament is practically infinite there will be no drop in voltage

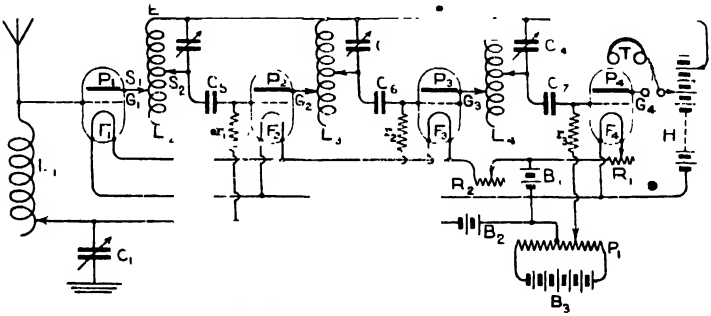


FIG. 161.—A four-stage detector-amplifier in which auto-transformers couple successive vacuum tubes. The figure also shows how the potentials of the grids can be varied in this class of circuit.

due to the resistance of r_2 (or r_3) and the grid potentials will be the voltage of B_2. A potentiometer might be used in place of B_2.* This method of applying potentials may be used in many amplifier circuits. In Fig. 161, the potential of the grid of the rectifying valve is shown being varied by a potentiometer P_1. Rectification at a bend of the anode current curve is thus obtainable.

Indirect Coupling of Vacuum Tubes in Cascade.—The most valuable method of coupling valves in cascade is the very obvious one of coupling the output circuit of one vacuum tube to the input circuit of another. The arrangement is shown in Fig. 162. An initial radio-frequency transformer L_1L_2 is shown and will eliminate a considerable amount of interference. The oscillations are amplified in the anode

* The positive side of B_2 is sometimes connected to a slide on a resistance connected across B_1. If there is a tendency for the amplifier to oscillate, B_2 is usually omitted.

oscillatory circuit L_3, which is aperiodic, and are thence induced into the grid oscillatory circuit L_4 of the second valve, which is also aperiodic. The coil L_4 may, if desired, be wound with resistance wire and have a fixed coupling with the coil L_4. The second valve is adjusted to act as a detector.

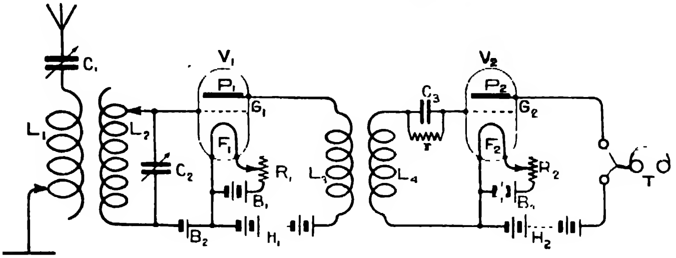


FIG. 162.—Use of a radio-frequency transformer to couple two valves.

This combination may be rearranged in a practical manner as shown in Fig. 163. This circuit is exactly the same as that of Fig. 162, except that single batteries are used. Both L_3 and L_4 are aperiodic and their coupling is fixed and is, if anything, tight. Since we have separated grid and anode oscillatory circuits, the former may be connected directly

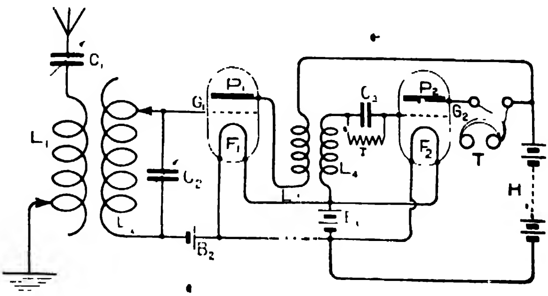


FIG 163.—Two-valve receiver employing a fixed aperiodic H.F. transformer between the valves.

across the grid and filament of the second valve, without the effect of the anode battery coming into the question. The windings L_3 and L_4 are usually wound in grooves cut into ebonite rod of large diameter.* Alternate grooves take primary and secondary, the alternate windings being in series. The grooves are separated to lessen capacity effects.

* Usually about two inches diameter.

Multi-stage amplifiers using more than two valves may be arranged on the principles previously employed, and no further illustrations are necessary. In the foregoing circuits, the last valve is used as a detector. The exact method of obtaining rectification is left to the reader. He can use a leaky grid, as has been shown in the figures, or he can simply connect the grid to the negative side of the filament and utilise the simple rectification obtained by means of grid currents; or, with the grid still connected to the negative side of the filament, he can decrease his filament current until the valve is operating at the initial point of saturation on the anode current curve.

Tuned Intermediary Circuits.—The intermediary circuits so far considered have been aperiodic. By connecting variable

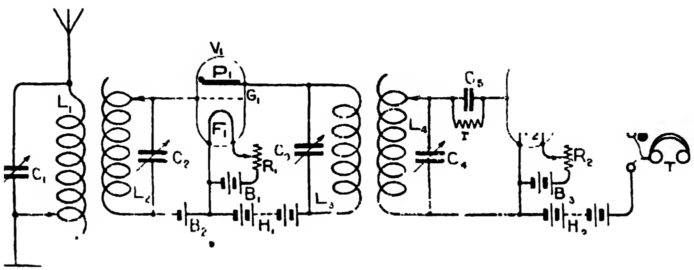


FIG. 164.—Selective circuit in which the detector is coupled to the amplifying vacuum tube by means of a tuned oscillation transformer.

condensers across the grid and anode oscillatory circuits we can tune them to the frequency of the incoming waves and thereby obtain better signals and much greater selectivity. The circuits, however, require careful adjustment and they are not very convenient to mount as a separate amplifier-detector.

Fig. 164 shows a circuit having high selective properties, the intermediary circuits being tuned.* A certain amount of interference is eliminated by the radio-frequency transformer L_1L_2, which is loosely coupled.

Amplified oscillations are set up in the tuned anode oscillatory circuit L_3C_3, and thence induced into the grid oscillatory circuit L_4C_4 of the second valve which is used as a detector. The loose coupling between L_3 and L_4 results in a further elimination of undesired signals. It has been shown that

* E. F. W. Alexanderson describes similar circuits in British Patent 147147 (Oct. 29/13).

if the desired signals are, say, three times as loud as the interfering signals, when two valves are used they will be 3^2 (nine) times as loud. If three valves were used in a similar manner they would be 3^3 (twenty-seven) times as loud. This is borne out in practice. In circuits of this type it is more important to tune the grid circuit of a valve than the anode oscillatory circuit of the preceding valve. The anode oscillatory circuits may conveniently be aperiodic if desired.

Tuning Intermediary Circuits.—The tuning of four oscillatory circuits will present a little difficulty, and the arrangement is therefore not very suitable for the general reception of signals. It is, however, in principle, ideal for use when receiving a fixed wave-length or when there is sufficient time to tune in. If the range of wave-lengths to be covered is not too great the inductances L_2, L_3, and L_4 may be made fixed, all tuning being accomplished by the condensers C_2, C_3, and C_4. Since all the circuits except the aerial circuit are independent of the aerial, they may be tuned together at the same time. The condensers C_2, C_3, and C_4 might all be made to rotate by simply turning one of them. The inductances L_2, L_3, and L_4 might also be varied together by turning one knob. By this arrangement, tuning would be greatly simplified and there would really be only two circuits to tune, the open one and the closed one.

A method, which may have a stronger appeal, of tuning the arrangement is to include the telephone receivers in the anode circuit of the first valve which is made to act temporarily as a detector by suitable adjustment of the filament current or anode battery. The condenser C_3 may be shorted and the aerial circuits and closed circuit L_2C_2 correctly tuned. The condenser C_3 is then unshorted and L_3C_3 tuned to give best results. In some cases tuning this circuit will make no difference to the signals heard, in which case it is unnecessary to short C_3 when tuning the first two circuits. When these are correctly adjusted, the 'phones are placed in their correct position in the anode circuit of the detecting valve; the first valve is made to act once more as an amplifier, and the circuit L_4C_4 is tuned to give the maximum response. The coupling between L_1 and L_2 and between L_3 and L_4 should at first be tight and then loosened when tuning has been effected.

Practical Arrangement of Tuned Intermediary Circuits.—A practical arrangement of the Fig. 164 circuit is given in Fig. 165

The anode oscillatory circuit L_3C_3 of the first tube is loosely coupled to the grid oscillatory circuit L_4C_4 of the second detecting valve. The inductances are shown fixed, but would be variable if the range of wave-lengths desired were wide.

Three-stage Detector-Amplifier with Tuned Circuits.—Fig. 166 is a development of Fig. 165, in that three vacuum

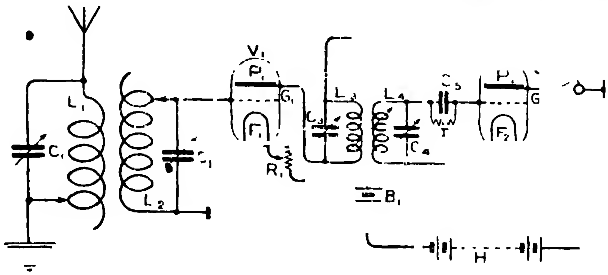


FIG. 165.—Practical two-valve receiver with tuned intermediary circuit

tubes are now employed, the first two being used as radio-frequency amplifiers and the last one as a detector.

The noticeable features of Fig. 166 are the use of a potentiometer P to vary simultaneously the normal grid potential of the amplifying valves, the use of a variable resistance R_2 to vary simultaneously the filament currents of the amplifying valves, the use of a separate rheostat R_1 for

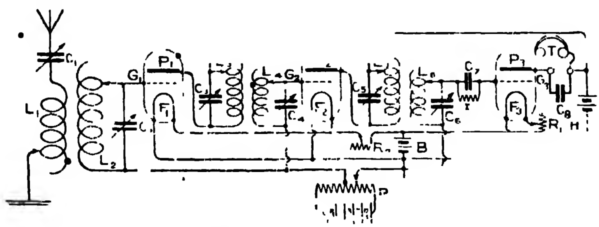


FIG. 166.—Practical three-valve detector-amplifier with tuned intermediary circuits

adjusting the voltage across the filament of the detecting valve, and, of course, the use of only one anode battery.

The use of the potentiometer P has its disadvantages, but it is given as an example of how to vary smoothly the grid potentials of the various valves. Instead of having a separate potentiometer it is preferable to replace P by a few cells and connect the potentiometer resistance across the filament battery B. The positive side of the grid battery is connected

to a sliding contact on the potentiometer resistance. This arrangement is of great use where a variation of only a few volts is desired.

One method of tuning such a complex circuit is to include the telephones first in the anode circuit of the first valve; tune the aerial and closed circuits. Then connect the 'phones in the anode circuit of the second valve; tune the circuits L_3C_3 and L_4C_4. Finally connect the 'phones in their normal position in the anode circuit of the last valve and tune the circuits L_4C_4 and L_5C_5. In the first two cases the rheostat R_2 may temporarily be adjusted to make the valves act as rectifiers. Now loosen all the couplings till "jamming" is sufficiently eliminated. This circuit is to be highly recommended, although usually the potentiometer P is an unnecessary refinement. A grid cell would do as well. For rapid tuning all the closed circuits may be calibrated in advance.

Prevention of Noise and Self-oscillation.—When using detector amplifiers of this kind, an unpleasant noise is frequently heard in the telephone receivers. This may be due to leakage of current. All the inductances through which the steady anode current passes should be very well insulated. Noises can generally be eliminated by decreasing the value of the anode voltage or by suitably adjusting the filament current of the valves.

Amplifier noises are of low-frequency. Consequently if the coupling between inter-valve oscillatory circuits is made loose, the variations are very considerably decreased although the high-frequency oscillations received will be easily passed on.

There is always a certain tendency for this type of circuit to oscillate of its own accord. A certain amount of retroaction undoubtedly is always present and precautions must be taken to prevent it causing the circuits to oscillate of their own accord. The potentiometer P of Fig. 166, if suitably adjusted, will effectually prevent self-oscillation. The reason for this is sometimes that the operating point on the anode current curve is altered. Frequently the potentiometer is connected across the filament accumulator. In this case, a positive potential is applied to the grids. This will set up grid currents, which will increase the damping in the grid circuits and thus prevent self-oscillation. The values of the anode voltage and filament current may also be varied to produce the same result. A less simple method is to connect a high-resistance (sometimes in series with a fixed condenser) across one or other of the grid oscillatory circuits; the consequent

damping produced will prevent the valves oscillating. Still another arrangement, which is rather simpler, is to couple a portion of, say, the coil L_5 to the coil L_4 in a reversed direction to counteract the retroactive effect. A resistance is sometimes connected in series with one of the tuning condensers.

High-frequency Amplification without Rectification.—It will be readily seen that any of the circuits from Fig. 155 to Fig. 166 may be used simply to amplify high-frequency oscillations without attempting to rectify them. All that is required is the substitution of an oscillatory circuit for the telephone receivers and a slight alteration of the circuit to make the last valve act in a way similar to the others. Fig. 167 is an example of a high-frequency amplifier with an output of radio-frequency current which may be used for a variety of purposes. This circuit is adapted from Fig. 166 in the

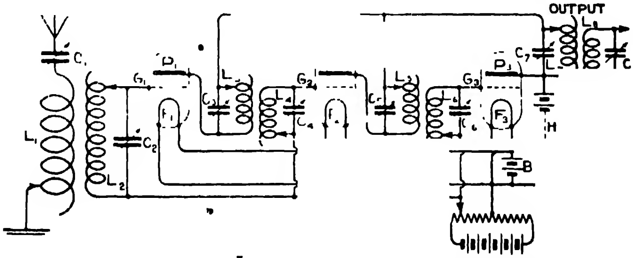


FIG. 167 —A three-stage amplifier of H.F. oscillations.

manner just described. All the valves are now used purely and simply as amplifiers.

It may be mentioned that such a circuit may be used for transmission purposes. In place of the aerial circuit shown on the left we could substitute, say, a small generator of electrical oscillations such as a tuned buzzer or an oscillating valve. The oscillations would be progressively amplified by each successive valve until considerable power could be drawn from the output circuit of the last valve, and induced through the radio-frequency transformer L_7L_8 into an aerial radiating circuit. When such a scheme is used, the intermediary circuits are not tuned.

Marconi Seven-Valve Amplifier.* -Fig. 168 illustrates a seven-valve amplifier detector produced by Marconi's Wireless Telegraph Company. The first six valves, which are of the V24 type, are used as high-frequency amplifiers and are

* See H. J. Round's British Patent 149433 (May 13/19).

coupled together by oscillation transformers whose windings are composed of very high-resistance wire. The effect of this resistance wire is to make the windings aperiodic so that the amplifier is equally sensitive over a wide range of wavelengths. The windings (primary and secondary) are run on to a bobbin simultaneously, so that the coupling is fixed and tight. It will be noticed that the grid and anode of successive valves are connected through a small condenser. This condenser helps to pass on the high-frequency impulses. The potentiometer enables the operator to vary the potentials

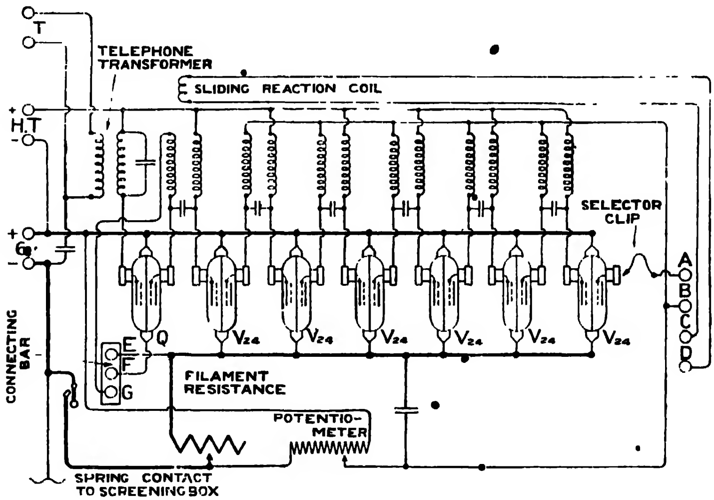


FIG. 168.—A Marconi seven-valve amplifier.

of the grids of the amplifying valves and so vary the tendency of the circuits to oscillate of their own account. The last valve is of the Q type and is used for rectifying. If desired, its grid potential may be altered by connecting a potentiometer across F and G while the filament current may be regulated separately by connecting a variable resistance across E and F. A connecting bar normally shorts these terminals. The terminals A and B are connected across the receiving circuit. A sliding "reaction coil" is provided to obtain retroaction with any of the inter-valve circuits.

Use of Inter-Valve Variometers.—In British Patent 148679 (June 27/19), H. L. Crowther describes an inter-valve oscillation transformer which is really a double variometer. A twin winding is used and one alteration of coupling varies the

wave-length of both primary and secondary windings.' An amplifier may thus be made to respond over a wide range of wave-lengths.

Use of Resistance Couplings.—A form of coupling between successive valves in an amplifier which has been of considerable use is that known as "resistance coupling." * A very simple form of this coupling is shown in actual use in Fig. 169. The anode circuit of the first vacuum tube consists of the anode P, the resistance R (a pencil-line or other resistance † of about 50,000 ohms), the battery H_1 and the filament F_1. A steady anode current is normally flowing through R accompanied by a considerable potential difference across the resistance. When incoming oscillations vary the grid potential of the first valve the current through R is varied at the same frequency. There

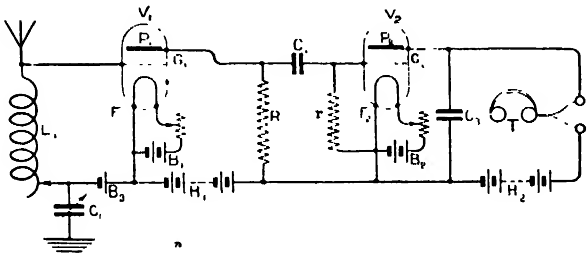


FIG. 169.—Illustrating the use of a resistance as a means of coupling two valves in a receiver

will consequently be oscillating potentials across R which are applied to a second valve arranged to act as a detector. A grid condenser C_2 is provided which has the additional duty of insulating the grid and thereby preventing it from taking up a normal negative potential equal to that across R. The small resistance *r*, the grid leak, if connected across C_2 would tend to defeat this object; it is therefore connected directly across grid and filament. The 'phones T are connected in the anode circuit of the second valve, and respond to the rectified signals.

It might be asked what value of R is the most suitable. The best theoretical value, of course, will be the one which results in the maximum potentials across its ends. We

* In British Patent 147617 (March 20/14), W. C. White (of G. E. C.) describes receiving circuits, using an ohmic resistance as the means of coupling the tubes (see also I. Langmuir in 147148 (Oct. 29 13)).

† S. R. Mullard has used a filament of partially carbonised cellulose as a resistance. These resistances are very constant and have been very extensively used for resistance amplifiers, grid leaks, etc. Blotting-paper soaked in Indian ink works well.

can represent the action of a resistance amplifier by reference to Fig. 170. P_1F_1 represents the apparent resistance of the anode circuit within the tube, measured by dividing the anode voltage by the anode current represented as a decimal of an ampere. G_2F_2 is a resistance which corresponds to R. A battery H passes a current through the two resistances in series. From the elementary principles of Ohm's Law we know that the voltage across G_2F_2 will be a fraction of H depending on the ratio of the resistance G_2F_2 to the sum of G_2F_2 and P_1F_1. This, after all, is the principle of the potentiometer. The greater we make G_2F_2 the greater will be the steady potential difference across this part of the circuit. Coming back to our valve, we see that if we make R equal to the internal resistance of the tube, the normal drop of potential across R will equal half the anode voltage. Thus if H possessed an E.M.F. of 100 volts and C_2 were shorted, the normal grid potential of the second valve would be —50 volts. This explains why a grid condenser is so useful. We are not, however, concerned with the *steady* potential drop in the anode resistance, but only the variation of the potential produce by a change in anode current consequent on a variation of grid potential. The grid really controls the resistance or impedance of the valve. A positive potential on the grid lessens the resistance, while a negative potential increases it. Variation of grid potential produces an effect equivalent to altering the value of the resistance P_1F_1 in our *explanatory* circuit of Fig. 170. Now, if the anode resistance G_2F_2 *is very much larger than the resistance of the valve* represented by P_1F_1, it is obvious that a fixed variation of the resistance P_1F_1 will produce little change in the voltage across the output resistance G_2F_2. Likewise, if the output resistance is much smaller than the valve resistance, small changes of voltage across G_2F_2 will result. The greatest amplification results when G_2F_2 is about equal to P_1F_1.

FIG. 170.—To demonstrate the action resistance for coupling purposes.

If we insert a resistance in the external anode circuit of the valve we will obviously have to increase the voltage of the anode battery in order to maintain the same anode potential. If the suitable anode voltage for ordinary amplification is 80 volts, the insertion of a coupling resistance equal to the internal resistance of the valve (say 100,000 ohms) will necessitate an anode battery of 160 volts to ensure the conditions being the same.

The most suitable value of the coupling resistance R will therefore depend on the internal resistance of the tube. If this is high, R will have to be preferably as high. In the case of most hard valves a resistance of 50,000 to 100,000 ohms has been found most efficient. A disadvantage of this type of circuit is that the anode battery requires to have an E.M.F. twice as great as that required with an ordinary circuit.

Effect of Valve Capacity on Resistance-coupled Circuits.—One great advantage of resistance-coupled amplifiers is that they have no intermediary oscillatory circuits which require tuning. The impedance of the resistance R is more or less equally effective for all wave-lengths, except the shortest. Short waves less than about 1,000 metres are not usually efficiently amplified on this type of circuit. This is because the impedance of R is decreased by the capacity between anode and filament within the valve itself. This capacity acts like a small condenser in parallel with R. The high-frequency current variations consequently do not meet with the same opposition as if the capacity effect were absent. A condenser may be considered as acting as a simple resistance towards high-frequency currents. The value of this resistance (usually termed reactance) in ohms,—

$$R = \frac{1}{2\pi nC}$$

where n = frequency of oscillations,

C = capacity of condenser in farads.

We see, then, that the greater the frequency of the oscillations, the less will be the resistance of the condenser, and vice-versa. For long waves, whose frequency is small, the capacity effect across R will not affect matters; but when short waves (whose frequency is high) are being received, the condenser effect inside the valve acts as a small resistance in parallel

with the resistance R. The effective resistance of R to the high-frequency currents is thereby lessened and the degree of amplification for short waves is therefore less than that in the case of long waves.

To lessen the capacity between filament and anode the various wire leads to the electrodes should be as far away as possible from each other, both inside and outside the bulb. When such special precautions have been taken the efficiency of the arrangement is increased.

By connecting a small variable condenser across R the phenomenon mentioned above may be used to lessen the interference from strong short-wave signals during the reception of long waves.

Summarised Features of Resistance Couplings.

(1) They are suitable for the amplification of long waves over about 500 metres.
(2) They require specially constructed valves if used for short-wave reception.
(3) They require an anode battery of about twice the voltage normally used.
(4) The value of the resistance should be about the normal internal resistance of the anode circuit (usually from 50,000 to 100,000 ohms).
(5) The use of resistance couplings eliminates tuned intermediary circuits which require careful adjustment.
(6) An amplification of about 8 times (for each valve) is theoretically possible with the ordinary valve.

A Practical Resistance-coupled Receiving Circuit.—Fig. 171 shows a practical receiving circuit based on Fig. 169. The resistance R is connected as shown and together with H forms the anode circuit of the first valve. The *oscillating* potentials across the anode and filament of this valve (which potentials are the same as those across R in Fig. 169, since the resistance of H is negligible) are applied across the grid and filament of the second valve. The anode circuit of the second tube includes the 'phones T, the anode battery H and F_2. Since the resistance of the anode circuit of the second valve is almost half that of the first one, the voltage on P_2 would ordinarily be too high. To avoid this we can :

(1) Tap a smaller voltage off the battery H as shown in the figure.

(2) Include a resistance almost equal to R in the anode circuit of the second valve.

(3) Use a telephone transformer with a very high resistance winding in the anode circuit.

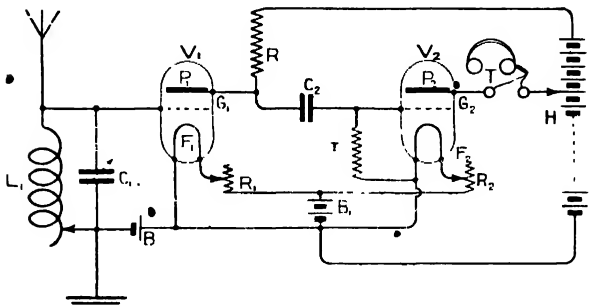


FIG. 171.—Practical two-valve resistance-coupled receiver.

The first suggestion seems the most practical, though it may lead to confusion in the case of an untrained operator.

Four-Valve Resistance-coupled Detector Amplifier.—A very useful circuit for the reception of weak signals is that given in Fig. 172. Four vacuum tubes are in use. The first three are intended to be used as amplifiers and have a common filament current rheostat R_4, the last valve having a separate

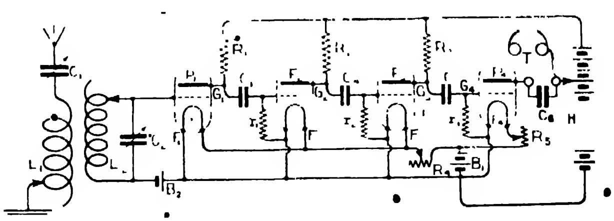


FIG. 172.—A sensitive four-stage resistance amplifier.

rheostat R_5; the voltage on the anode of the last valve is also adjustable. There can be no doubt that a certain amount of rectification takes place in the anode circuit of the second and third valves, but this is no disadvantage.

The anode circuit resistances R_1, R_2, and R_3 have all the same value (about 80,000 ohms for most small hard vacuum

tubes). The grid leaks r_1, r_2, r_3, are also all of the same value, namely about 3 megohms, though this will depend largely on the type of valve used.

Resistance Amplification without Detection.—If we desire to obtain amplified oscillations without rectification we can use a circuit similar to that of Fig. 173. In this figure, A is some source of the oscillating current which requires amplification. R is a resistance in the anode circuit of the first valve. A variable tapping S enables the power developed in the anode circuit of the second vacuum tube to be varied, since by its means the potentials applied to G_2 may be varied; the maximum power is obtained when S is at the top end of R. The anode circuit of the second valve, which would be larger than

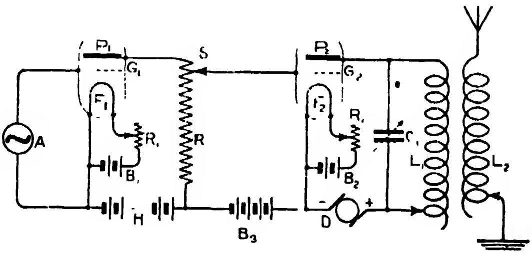


FIG. 173.—Use of a resistance to vary the output of an amplifying vacuum tube.

the first if it had to deal with heavy currents, includes an oscillatory circuit L_1C_1 and a source D of high potential, which might be a direct current dynamo. The oscillatory circuit L_1C_1 is shown coupled to a radiating circuit. The battery B_3 is connected with its negative pole to the grid G_2 and is given a value to make G_2 sufficiently negative to operate V_2 at a suitable point on its anode-current curve. For very small powers B_3 may be reversed, since the drop across R may make G_2 too negative. The steady potential difference across this portion of R does not then adversely affect the normal grid potential of G_2. The battery B should preferably be less to give the grid a negative potential.

Another practical application of resistance coupling is shown in Fig. 174, which shows incoming oscillations being amplified by three tubes which are not intended to rectify. The amplified oscillations are drawn off from an anode

oscillatory circuit L_3C_3. In the figure the amplified oscillations are shown operating a crystal detector D.

Instead of using the condensers C_3 and C_4 and the grid leak resistances r_1 and r_2, we might connect batteries with their negative poles to the grid. These batteries would neutralise the effect of H. Since they would have to have a voltage about half that of the main anode battery, their use is not very convenient. The coupling resistances in this figure are shown variable. All the previous circuits may have variable resistance couplings if desired. Resistance amplifiers have been largely developed by Brillouin and Beauvais. (See British Patent 127013.)

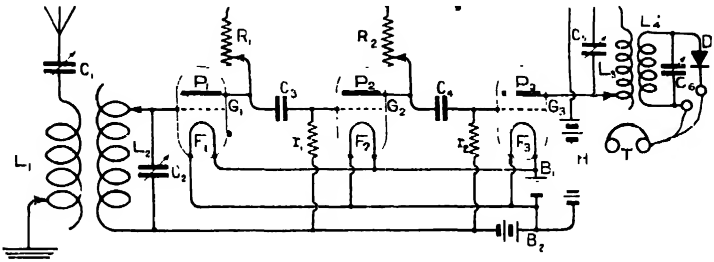


FIG. 174.—A resistance-coupled series of vacuum tubes used for pure H.F amplification. The output circuit L_3C_5 is shown coupled to a crystal detector circuit.

Resistance amplifiers may be used for the elimination of certain frequencies, while other wave-lengths are fully amplified. These uses are described by N. Brillouin in British Patent 131054 (Oct. 8/17).

Use of Vacuum Tubes as Inter-valve Resistances.—Various kinds of resistances have been suggested for use in amplifier circuits of this kind. One kind, however, is of special interest. It consists of an anode and filament mounted in a vacuum bulb. The filament is heated to incandescence and the arrangement acts as a unidirectional conductor of high resistance. The actual resistance may be varied by altering the filament current.*

G.E.C. Valve Resistance Amplifier.—In British Patent 5373/15 (April 9/15), the General Electric Company of U.S.A. describe the circuit shown in Fig. 175. Instead of using grid

* J. Scott-Taggart, *Electrical Review*.

condensers to prevent the normal grid potential from being affected by the anode battery of the previous vacuum tube, grid batteries are employed. In Fig. 175 the amplified oscillations are passed through a tuned radio-frequency transformer L_3L_4 connected to a detector vacuum tube. The tube V_2 is not

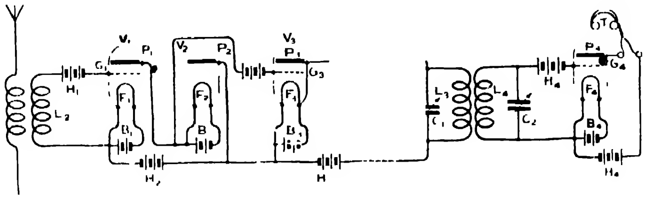


FIG. 175.—Use of valve as resistance coupling (G.E.C.).

only used as a resistance, but also as a current-limiting device to limit the effect of strays, etc.

Further Circuits Employing Valve Resistances.—In addition to the circuits described above, the present author has devised a number of effective circuits working on a similar principle.

One arrangement is shown in Fig. 176. The anode

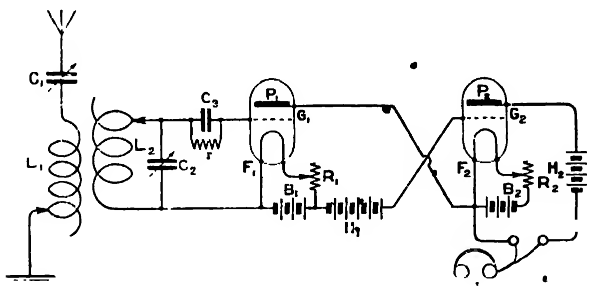


FIG. 176.—Two valves arranged in cascade, using the filament to grid path of second valve as the resistance (J. Scott-Taggart).

current of the first valve passes from P_1 to F_2, thence to G_2, H_1, and F. The battery H_1 may be omitted if the other connections are left as shown. The best results are obtained, however, when H_1 is used.

Maintaining Normal Grid Potentials in Resistance Amplifiers.—One of the important problems in the design of resistance amplifiers is the avoidance of communicating the potential drop across the resistance to the grid of the succeeding valve. When a single common anode battery is employed the use of

grid condensers overcomes the difficulty, but this arrangement only lends itself to the amplification of high-frequency currents. By making the condensers very large, low-frequency currents may be amplified. If we desired to amplify a steady potential we would have to replace the grid condensers by batteries connected so as to oppose and neutralise the effect of the anode battery. If each valve has a separate anode battery, other methods may be employed. We can, for example, connect the grid and filament of the second valve across the anode resistance and a point on the anode battery of the previous valve. An example of this method is shown in Fig. 177, which illustrates British Patent 127651 (May 12/17) of Marconi's Wireless Telegraph Co. and G. M. Wright.

The included portion of the anode battery is made to

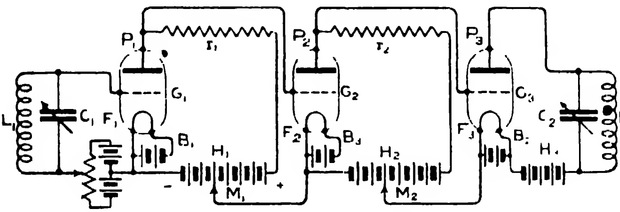


FIG. 177.—Wright's resistance amplifier

balance exactly the potential drop across the anode resistance. The potential of the second grid is consequently zero. Another arrangement is to split the anode battery into two sections and to place the anode resistance between the two sections. Leads to the second valve are taken from the filament and the anode end of the anode resistance of the first valve. This arrangement is described incidentally in one of Marius Latour's specifications.*

Use of Choke-coil Couplings. A form of intervalve coupling which may be compared to that utilising resistances, is that which employs a choke-coil in the anode circuit of one valve and applies the oscillating potentials across it to the grid of a second valve. Such an arrangement is shown in Fig. 178. The anode circuit of the first valve consists of P_1, a choke coil Z having an iron core, an anode battery H_1 and the filament F_1. A steady current will easily flow through Z, which, however,

* British Patent 148995 (Dec. 16/18).

offers very considerable impedance to the high-frequency potentials established when signals are being received. These radio-frequency potentials are consequently impressed on the grid of the second valve through the medium of the grid condenser C_2. This second valve acts as a detector and signals are produced in the telephones T.

Features of Choke-coil Coupled Amplifiers.—The choke-coil Z may be of quite low direct current resistance, say, 1,000 ohms. This resistance is very small compared to the internal resistance of the valve, so that only a normal value of anode voltage is required, whereas a much larger anode battery was required for use with the resistance amplifiers just described.

Another advantage of choke-coils is that the steady drop

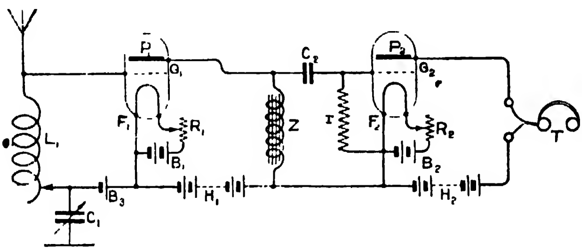


FIG. 178.—Receiving circuit in which the two valves are coupled by means of a choke-coil Z.

of potential across Z is small since the direct current resistance is almost negligible compared to the resistance of the valve. If, then, we connected the grid and filament of a second valve directly across Z, the grid of this second tube would only receive a potential of about —1 volt, instead of about —50 volts as in the case of a resistance amplifier. This advantage allows us, if we like, to dispense with stopping condensers.

A third peculiarity of choke-coil amplifiers is that their importance depends on the impedance offered by iron-core chokes to high-frequency currents. This impedance

$$Z = \sqrt{(2\pi n)^2 L^2 + R^2}$$

where : n = frequency of oscillations
L = inductance of choke-coil
R = resistance of choke-coil.

We see from this that the greater the frequency of the incoming oscillations, the greater will be the impedance offered to their

passage by the choke Z. Now since the effectiveness of the amplifier depends on the impedance offered to oscillating current, we will see that the arrangement of Fig. 178 will be more effective for short waves than for long waves: this peculiarity makes a choke-coil amplifier useful where a resistance amplifier would be almost useless. The desirability of using vacuum tubes of small internal capacity still holds good, but the matter is not of the same importance as before.

We can summarise these points as follows:—

(1) The resistance of the choke to direct current is small; consequently, an ordinary anode battery is suitable.

(2) The steady potential across the choke-coil is only about 1 volt, so that stopping condensers in succeeding grid circuits are unnecessary when the valves are in series.

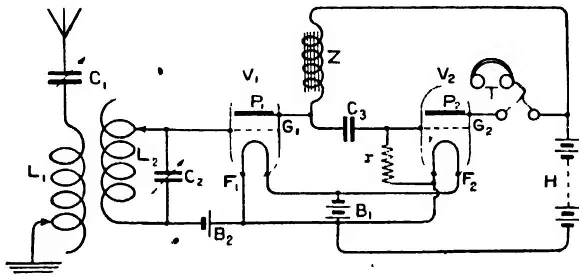


FIG. 179.—A two-valve receiving circuit in which valves are coupled by a choke-coil.

(3) Choke-coil amplifiers are most efficient for receiving short waves since the impedance of the choke is highest for these waves.

Practical Choke-coil Circuit.*—Fig. 179 shows a two-valve choke-coil receiver adapted from Fig. 178 for use with one anode and filament battery. The circuit needs no further explanation. Oscillating potentials at the foot of Z are impressed on the grid of the second valve, which acts as a detector.

An Oscillation Amplifier.—Fig. 180 shows the use of a choke-coil amplifier to magnify oscillations supplied by a source A. This class of circuit is of interest since it shows again how single anode and filament batteries may be employed.

* See J. Scott-Taggart, "Use of Impedance Capacity and Resistance Coupling in Amplifiers," *Wireless World*, Feb. 1919.

Use of Iron-core Transformers.—We have already seen the use of radio-frequency transformers in between the vacuum tubes of a high-frequency amplifier. Marius Latour * has

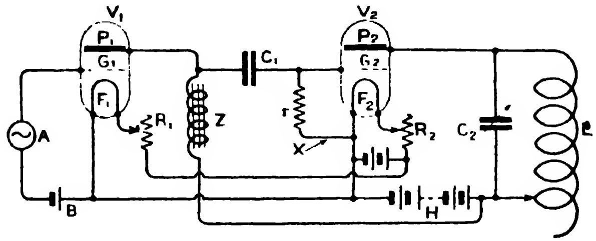


FIG. 180.—A high-frequency amplifying circuit using an impedance coupling.

described the use of iron-core transformers tuned to the radio frequency as intermediary couplings between valves in cascade.

The basic circuit is shown in Fig. 181. Incoming oscillations set up magnified oscillations in the anode circuit of the first valve which includes the primary winding T_1 tuned by means of a large variable condenser C_2 to the frequency of the oscillations passing through it. The oscillations passing

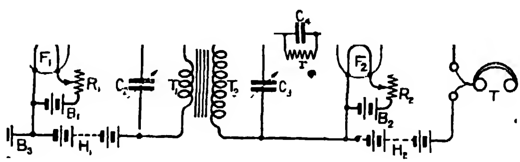


FIG. 181.—Use of an iron core transformer tuned to high frequencies as a means of coupling two valves.

through T_1 induce similar oscillations in the winding T_2, which also is tuned to the incoming frequency by means of C_3; the transformer T_1T_2 may conveniently be of the step-up type in order to increase the potentials applied to the grid of the second valve, which is shown acting as a detector.

Tuning condensers are sometimes omitted.

Features of Iron-core Coupling Transformers.

(1) They are highly selective.

(2) By the use of step-up transformers potentials may be

* Marius Latour, *Electrician*, May 23, 1919. Also British Patent 127318 (April 16/17).

increased before being applied to the grid of the next valve.

(3) They require expert designing and are not likely to be of interest to the average experimenter.

(4) They are specially suited for long-wave reception, owing to the high-inductance of the windings.

As evidence of the efficiency and selectivity of this type of amplifier, Marius Latour states that a six-valve amplifier was connected to a few turns of wire wound round a former a few feet in diameter and signals were received at Lyons from Annapolis; by suitable adjustments the local high-power station of Lyons, a mile distant, could be completely tuned out, although working on a wave-length only $2\frac{1}{2}$ per cent. different from that of Annapolis.

Electrostatically Coupled Amplifiers.—This class of coupling is not of great interest and it is only proposed to show

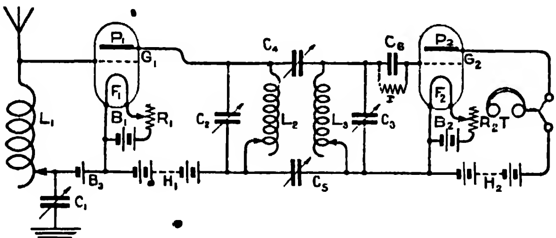


FIG. 182.—Showing capacitative coupling between two valves.

one example of its use. Fig. 182 shows the output circuit of one valve coupled to the input circuit of a detecting valve by means of the condensers C_4 and C_5, no magnetic coupling existing between L_2 and L_3. Only one condenser may be used if desired, the other being shorted.

Separation of Oscillatory Circuit from Direct-current Anode Circuit.—A type of circuit frequently used is that shown in Fig. 183 (*a*). H is the anode battery with a high non-inductive resistance R in series with it. The oscillating potentials across P and F are communicated through the coupling condenser C_2 to the anode oscillatory circuit L_2C_2. No direct current now passes through the inductance L_2, but only oscillatory current. The resistance R is of about 100,000 ohms. This circuit is similar to one described by the Western Electric Company (U.S.A.) in British Patent 102500 (Nov. 29/1915).

As we have already seen, Roy A. Weagant has used a choke-coil in place of R which may conveniently consist of the telephones, if it is not desired to couple L_3 to another valve (Fig. 183(*b*)).

Arco and Meissner have suggested the type of circuit shown in Fig. 183(*c*). The direct anode current passes through the choke-coil Z, the oscillatory current passing through $C_3L_3C_4$.

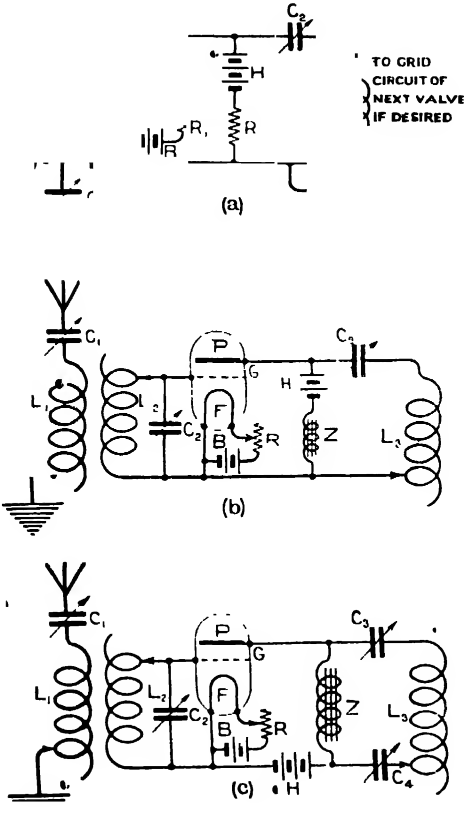


FIG. 183 (*a*), (*b*), (*c*).—Methods of separating the H.F. current from the steady anode current.

In all these circuits it makes little difference whether the anode oscillatory circuit is across anode and filament or merely across the resistance R or choke-coil Z. If the circuit of Fig. 183(*b*) is used, care must be taken not to short C_3, otherwise H will discharge through L_3 and Z. As a general principle (particularly when dealing with valve transmission circuits) it is preferable to avoid allowing the high-frequency currents to pass through the anode battery. It is therefore advisable when separating the two circuits to connect the oscillatory circuit across the anode and filament of the valve.

In any of the circuits of Fig. 183, the anode oscillatory circuit may be coupled directly or indirectly to the grid circuit of another valve to obtain further amplification.

CHAPTER VII.

MULTI-STAGE LOW-FREQUENCY AMPLIFIERS.

In the preceding chapter we have considered the use of vacuum tubes in cascade as amplifiers of high-frequency oscillations. These amplifiers for the most part are not suitable for magnifying current variations of low frequency. The resistance amplifiers would be suitable, but since they have already been discussed it is not necessary to repeat what was said before.

Lee de Forest was one of the first to use valves in cascade for amplifying purposes, and he describes one arrangement in British Patent 2059/14 (June 21/13).

Use of Iron-core Transformers between Valves.—The best form of coupling between successive valves in a low-frequency amplifier consists of a step-up transformer. The design of this transformer is of utmost importance. Different commercial types of amplifier vary a very great deal in the number of turns, resistance, ratio, etc., of their transformers, but definite values are given as examples.

Two facts are of interest. The use of iron-core transformers allows us to step-up the voltage variations in the anode circuit of one valve before applying them to the grid of the next valve. We can consequently get very considerable magnification. We can also tune our transformers to a definite note frequency and thereby eliminate interference to a certain extent. Some transformers are tuned to a frequency of about 1000, while in the case of others no attempt is made to resonate the transformer to any special frequency.

A Two-valve Low-frequency Amplifier.—Fig. 184 shows the basic circuit of a simple two-valve amplifier. An input transformer T_1T_2 is of the step-up type, having a ratio, say, of 1 to 10. From the point of view of efficiency closed-core transformers have been found best, although less distortion of the current variations is experienced with those having open cores. The greater the resistance of the circuit to which T_1 is connected, the higher should be the resistance of the winding T_1. The reader will usually be using a low-frequency amplifier to magnify the rectified current

obtained from a valve detector, in which case the winding T_1 will take the place of the telephone receivers. Since the resistance of the anode circuit is high, the resistance of the winding T_1 should also be high. If, however, we make it too high, we not only make the construction of the transformer more difficult but our action will necessitate the use of a larger anode battery in the circuit in which T_1 is included. A resistance of from 500 ohms to 8,000 ohms will be found appropriate. The winding T_1 may be tapped off into sections if desired.

The winding T_2 will usually have a much higher resistance. The stepped-up voltages across this winding are applied to the grid and filament of an amplifying valve. A small cell B_3 is

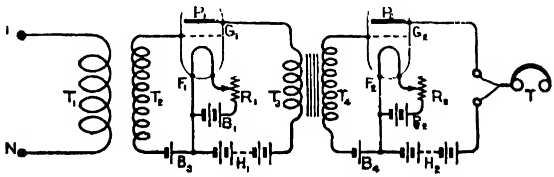


FIG. 184.—A two-valve low-frequency amplifier.

connected in the grid circuit to increase the efficiency of the valve as an amplifier by preventing damping due to the establishment of a grid current. In the anode circuit we have the primary winding T_3 of a step-up transformer T_3T_4, which may have a ratio of about 1 to 5. The secondary T_4 of this transformer is connected across the grid and filament of a second amplifying valve in the anode circuit of which we connect the telephones T.

Graphical Representation of L.F. Amplification.—Fig. 185 shows graphically the amplification which goes on in a simple two-valve low-frequency amplifier. The first line shows the original current variations which may conveniently be considered as being of the nature of alternating current. The voltage of the alternating current is stepped up by the transformer T_1T_2. The grid potential of the first valve is therefore varied as shown in the second line. This causes magnified variations in the anode current shown in the third line. These variations are stepped-up and applied to the grid of the second valve, the potential of which consequently varies as shown in the fourth line. The bottom line of Fig. 185 represents the final current variations, which affect the telephones T in the anode circuit of the second valve.

Practical Two-valve L.F. Amplifier.—Fig. 186 shows a simple rearrangement of the theoretical two-valve circuit we have just been discussing. It should be carefully noted how one grid cell is used to give both grids the same negative potential; how one anode battery and filament-heating accumulator are used; and how one filament current regulator R varies the filament current of both valves at the same time. These arrangements can be so made, since both vacuum tubes are being used as amplifiers under exactly the same conditions. This is poss[illegible]nly because the manufacture of

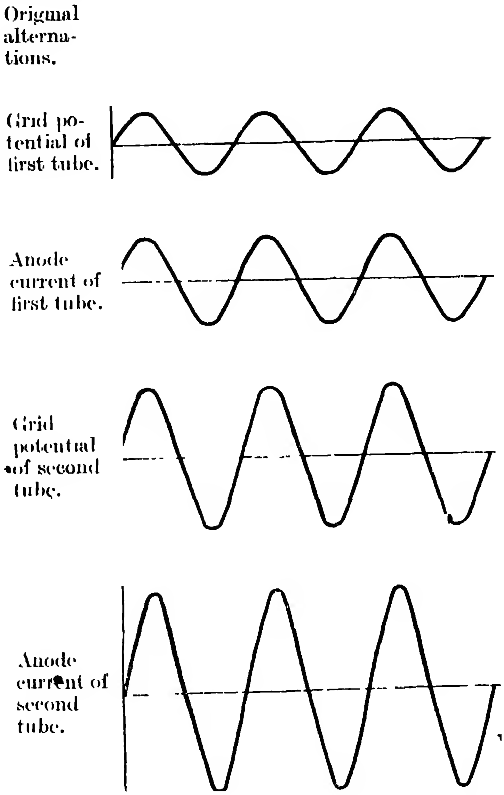


FIG. 185.—Graphical representation of the amplification obtained with a Fig. 184 circuit.

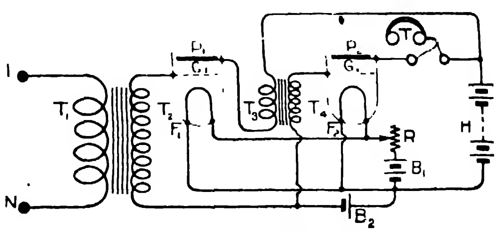


FIG. 186.—A practical two-stage L.F. amplifier.

vacuum tubes has reached such a degree of perfection that

any two valves of the same make can usually be relied upon to have almost the same characteristics.

The anode circuit of the first valve consists of P_1, T_3, H, and thence to the filament F_1. Current variations in T_3 are stepped-up in T_4 and applied to the grid of the second valve which, together with that of the first, should preferably be kept at a negative potential by means of a small dry cell B_2, one or two cells with a switch, or a potentiometer connected in place of B_2. Magnified current variations pass round the anode circuit of the second vacuum tube which consists of P_2, the telephones T (or the high-resistance winding of a telephone transformer, if the latter is used), the battery H, and thence to the filament F_2 of the second valve.

The operation of the device simply consists in adjusting the anode voltage by means of H, which is usually variable in steps of about 10 or 15 volts, and the filament current rheostat

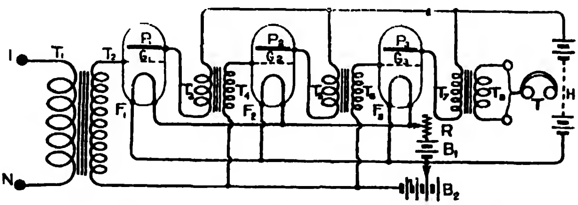


FIG. 187.—A practical three-valve L.F. amplifier.

R until the necessary strength of signals is obtained. The maximum strength is usually obtained when the values of both filament current and anode voltage are high. The anode current curve is rather more steep under these conditions. On a certain class of valve, 4 volts across the filaments and 70 volts on the anodes gave the loudest results. Quite good results, however, are obtained with smaller anode voltages, such as 20 volts, but the filament current should be decreased at the same time. These two adjustables should always be varied together in the same direction; the reason is that by so doing we keep the operating point on the same relative position on the anode current curve, this position being such that the representative point does not leave the steep straight portion of the curve when the amplifier is in action.

Three-valve L.F. Amplifiers.—Fig. 187 shows a diagram of a practical three-stage low-frequency amplifier. It is the obvious development of the practical two-valve amplifier.

Instead of passing the amplified current variations through our 'phones we pass them through a step-up transformer T_5T_6, the secondary of which is connected across the grid and filament of a third vacuum tube.

The Fig. 187 circuit is essentially a practical amplifier for general use on a wireless receiving station. All three filaments are heated through a variable resistance R (max. 5 to 10 ohms) by a four or six-volt accumulator B_1. The winding T_1 is of high resistance, say, 3,000 ohms, and will generally be included in the anode circuit of a rectifying valve. The transformers T_3T_4 and T_5T_6 are inter-valve step-up transformers having a ratio of between 1 to 5 and 1 to 10. The potential of all three grids is adjusted to a negative value by means of a battery B_2, variable by means of a radial switch in steps of 1·4 volts (the voltage of each cell).

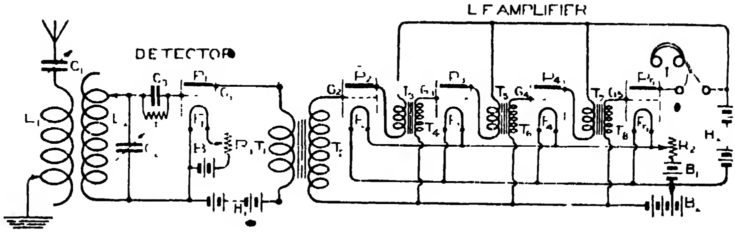


FIG. 188.—A four-stage audio-frequency amplifier connected to a wireless receiving circuit.

A potentiometer is not recommended since the cells in it usually last only a short time. A single grid cell usually suffices.

A telephone step-down transformer T_7T_8 is included in the anode circuit of the last valve. This is preferable to having the telephone receivers directly in that circuit. In any valve circuit such a transformer may be used in place of the 'phones with advantage.

An amplifier of the above type is of very great use as a separate instrument which can be connected to any receiving detector circuit. It may be mounted in a box or on a baseboard provided with six terminals; two for the transformer winding T_1; two for the filament heating accumulator, and two for the anode battery, unless the latter is small and can be mounted in the same box as the amplifier itself.

A Four-valve L.F. Amplifier.—Fig. 188 shows the arrangement of a four-valve amplifier, which is probably the most

useful kind when used in conjunction with a single detecting valve. In the figure is shown the manner in which a low-frequency amplifier is usually employed.* The advantage of using a detector valve followed by a number of amplifying valves is that tuning is very quickly accomplished. There are no tuned intermediary circuits; the amplifier works equally well for any wave-length. On the other hand the arrangement is not as efficient as it appears. By using such a circuit weak signals are not very efficiently received since the first valve does not rectify such signals to any extent. For strong signals, or where we desire to reproduce already good signals on a still louder scale for some special purpose, the circuit is good. But modern endeavour should be in the direction of the elimination of interference and the reception of very weak signals over long ranges; for this purpose the circuits of the previous chapter are to be preferred.

The Elimination of Noise in Amplifiers.—One of the difficulties of amplifier design consists of the elimination of various sizzling, crackling, or howling noises which frequently are heard in amplifiers having several valves. These noises are due largely to the following causes:—

(1) Faulty insulation of the amplifier.
(2) Transformer leakages.
(3) Eddy currents in iron cores.
(4) Uneven discharge of filament heating battery or anode battery.
(5) Faulty anode battery.
(6) Microphonic noises due to vibration.
(7) Undesirable capacity effects.
(8) Leakage of current through the operator; faultily insulated telephone receivers.
(9) Self-oscillation of the valves.
(10) Defective vacuum tubes, such as those having grids or anodes which are not rigid.

The noises due to the above effects may sometimes drown the signals actually being received. They can usually be eliminated by decreasing the filament current, thereby bringing us on to a less steep portion of the anode current curve; at the

* The same anode battery and filament accumulator may be used instead of having separate ones. This applies to the combining of all circuits in which the anode battery comes next to the accumulator.

same time, however, the signals are also weakened, although usually not quite to the same extent.

The greatest care should be exercised in insulating all parts of the amplifiers, particularly the transformers, which usually give most trouble. Noises can frequently be lessened by connecting the iron cores of the transformers all together by means of a wire, which is then connected to the positive pole of the anode battery. The amplifier may also be made to function more quietly sometimes by connecting together the two bottom ends of the windings of the input transformer; in other words connecting one or other of the input terminals (found by trial) to the negative side of the filament-heating battery. This battery should preferably be large (say, 80 ampere-hours) to obtain a more uniform discharge. Small accumulators are apt to discharge somewhat erratically. Moreover, the use of a large accumulator will not necessitate the continual readjustment of the rheostat R. The anode battery also should be fairly large, although a small one may be more convenient. Anode batteries composed of very small cells are usually troublesome, and soon run down. The very greatest care should be exercised in insulating each cell in the battery.

Microphonic noises are those heard in the 'phones when the valves of an amplifier vibrate. If the first valve of a three-stage amplifier is tapped, a loud click is usually heard in the telephones. This is a good sign as it shows that the amplifier s in a sensitive condition. Trouble, however, is experienced when the table on which the amplifier may stand is caused from some reason or other, to vibrate. Crackling noises are heard in the receivers. These may be eliminated by standing the amplifier on shock-absorbing rubber legs or by suspending the valve holders on rubber cords.

Undesirable capacity effects, which frequently produce singing noises, may usually be prevented by separating the various leads and parts of the amplifier as much as possible. Sometimes, as in certain German amplifiers, each transformer is completely encased in closed copper cylindrical cases, which are all earthed or connected to some point of the circuit.* The British Marconi Company enclose their seven-valve amplifier, Type 55, in an enamelled tin box to screen it from outside effects.

Needless to say, the telephone receivers should be carefully

* See British Patent 148183 (Nov. 16 15).

insulated from the metal casing and head-band as well as internally. Connecting the 'phones in the main anode circuit very soon destroys the insulation and it is far more economical in the end to use a telephone step-down transformer. A good proportion of the noisiness of valve circuits is due to badly insulated telephones. A pair of 'phones should never be worn for more than a few hours at a time ; it is then desirable to change them, hanging up the used pair to allow the moisture condensed in them to evaporate. If the 'phones are leaking, the noises heard can frequently be stopped if the operator lifts his feet off the ground or otherwise insulates himself.

Sometimes the valves of an amplifier commence to generate oscillations of their own accord. The oscillations are usually of various harmonic frequencies and account for the fact that continuous wave signals are sometimes accidentally received. Sometimes the valves oscillate at a low frequency, producing a continuous howling noise. Self-oscillation can usually be stopped by lessening the filament current. The valves generally tend to oscillate at frequencies well above audibility, that is, at a frequency of more than about 10,000. The phenomenon of self-oscillation is usually only met with when the amplifier is being used in connection with a circuit receiving long waves ; this, of course, is because the natural wave-length of the transformer windings is long on account of the high value of the inductances. Self-oscillation under these conditions may be prevented by connecting a fixed condenser and a non-inductive resistance in series with it across the grid and filament of the first amplifier valve, or of any of the succeeding valves as may be found best. A positive potential on the grids will also usually prevent oscillation through a damping effect, but signals will be decreased.

The effectiveness of an amplifier depends largely on the uniform characteristics of the vacuum tubes used. Sometimes one of the valves functions a little differently from the others or is defective. If then an amplifier is noisy, changing the relative positions of the valves or trying fresh ones, may result in the more efficient working of the circuit.

Use of Auto-transformer Couplings.—Instead of the transformers discussed above we might use auto-transformers for certain purposes. A portion of a single winding is included in the anode circuit of a valve and the whole winding may be connected across grid and filament of the next tube.

Degree of Amplification Attainable.—The student must realise at this stage that amplification cannot go on for ever merely by adding more and more valves to a circuit. Complications soon set in. The slightest leakage anywhere would cause a roar in the telephones of, say, a twelve-valve amplifier which would magnify various parasitic noises which are heard even on a three-valve instrument. If signals are very weak to begin with, the various noises will probably completely drown the signals and further amplification will increase the strength of the disturbances even more than the signals. Quite apart from this practical question, the degree of amplification is limited by the characteristics of the type of valve used. The maximum amplification is obtained when the varying grid potential varies the anode current from saturation value to zero. If this happens, say, at the eighth valve, the following valves cannot amplify, but merely distort the wave-form of the current variations. If we desired a very high degree of amplification we have consequently to use a larger size of valve after the eighth, or connect valves in parallel. Alternatively we might increase the anode potentials of successive valves.

CHAPTER VIII.

COMBINED HIGH AND LOW-FREQUENCY AMPLIFIERS.

Detector-Amplifiers.—A form of detector-amplifier which has been foreshadowed is that which consists of a detecting valve followed by one or more low-frequency amplifying tubes. The advantages and disadvantages of this arrangement have been already given. The chief advantage lies in the convenient arrangement of the circuits which lend themselves to being made up in the form of compact instruments requiring no adjustments.

The fundamental circuit of this type of amplifier is shown in Fig. 189. The first valve acts as a detector. The low-

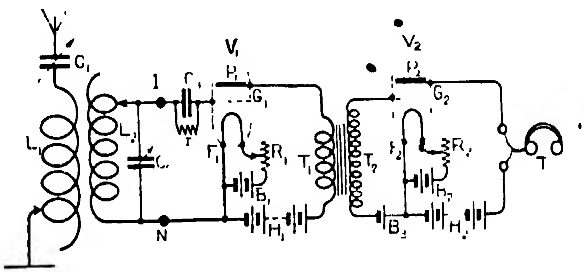


FIG. 189.—Two-valve receiver consisting of a rectifying valve followed by one acting as a L.F. amplifier.

frequency variations of anode current are stepped up by the transformer T_1T_2 and amplified in the second vacuum tube.

Fig. 190 shows how this circuit may be altered into a practical detector-amplifier. The input terminals I, N are shown connected to a simple receiving circuit. A fixed condenser C_3 is shown across T_1. This usually improves the strength of signals. The negative side of H may with advantage always be connected to the *positive* side of B_1.

A Three-valve Detector-Amplifier.—A three-valve detector-

amplifier is shown in Fig. 191. The first valve is acting as a detector and the second and third as amplifiers of the rectified signals. A small fixed condenser C_2 in the anode circuit of the rectifying valve usually strengthens the signals somewhat. This condenser is an advantage in all anode circuits of rectifying

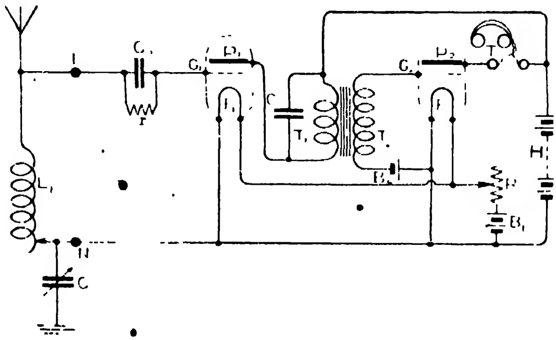


FIG. 190.—A two-valve detector-amplifier circuit connected to the oscillatory circuit of a receiver.

valves. It by-passes the high-frequency component of the anode current of the detector valve in addition to its low-frequency functions. A telephone transformer is shown connected in the anode circuit of the last valve. The filament current of the rectifying valve is shown variable by means of a separate rheostat R_1.

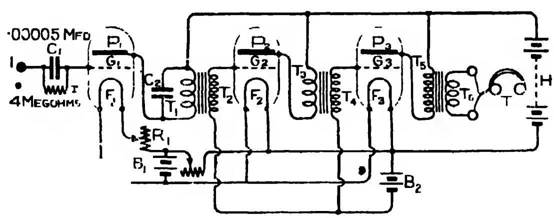


FIG. 191.—A practical three-stage detector-amplifier.

Combined High- and Low-frequency Amplifiers.—The reader, no doubt, will by now have realised that a combination of high- and low-frequency amplification is possible with the aid of three valves, as shown in Fig. 192. The coil L_3 in this figure is shown roughly aperiodic, but it might easily be tuned by connecting a variable condenser across it.

Fig. 193 shows the same circuit in practical form. The first valve acts as a high-frequency amplifier, the oscillations taking place in the circuit L_2C_2. The second valve is fitted with a leaky grid condenser C_3, which rectifies the oscillating potentials impressed on the grid. The rectified pulses which are stepped-up by the transformer T_1T_2 are amplified by the

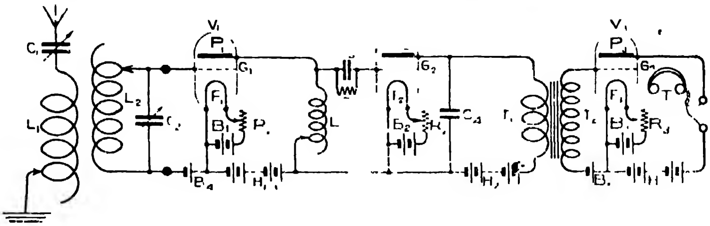


FIG. 192.—Receiving circuit in which V_1 acts as an oscillation amplifier, V_2 as a detector, and V_3 as a L.F. amplifier.

last valve. It will be seen that since the first and third valves act as amplifiers (the first as a high-frequency and the last as a low-frequency amplifier), the same rheostat R_1 will serve to regulate their filament currents. The rheostat R_2 is a separate one used for regulating the current through the filament of

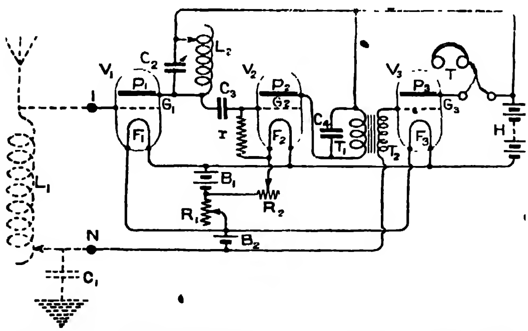


FIG. 193.—Practical form of circuit shown in Fig. 192.

the rectifying valve. The grid cell B_2 is arranged to give the grids of the first and third valves a negative potential.

This type of amplifier is very suitable for the reception of weak signals, which are first strengthened by the first valve before being applied to the detecting valve.

A Four-valve Combined Amplifier.—Fig. 194 shows a four-valve amplifier designed on similar lines, but having aperiodic

indirectly-coupled oscillatory circuits between the first two valves, which are acting as high-frequency amplifiers. The third vacuum tube acts as a detector and the last one as a low frequency amplifier of the currents rectified by the third valve. As before, the rheostat R_1 varies the filament current

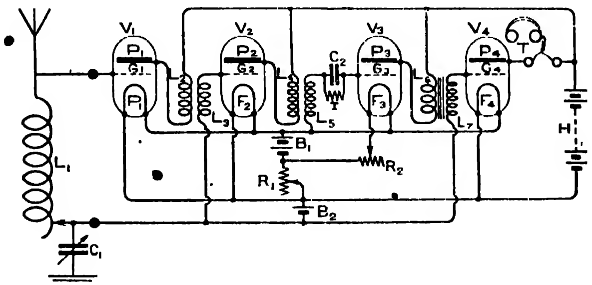


FIG. 194.—A four-valve receiver combining H.F. amplification, detection, and L.F. amplification.

of the 1st, 2nd and 4th valves, all of which act as amplifiers. The amplifier is shown connected to a simple receiving circuit.

Combined Resistance and L.F. Amplifier.—It is obvious that we could use a receiver consisting of a resistance amplifier followed by a low-frequency amplifier. Such a circuit is shown in Fig. 195. The first vacuum tube acts as a high-frequency

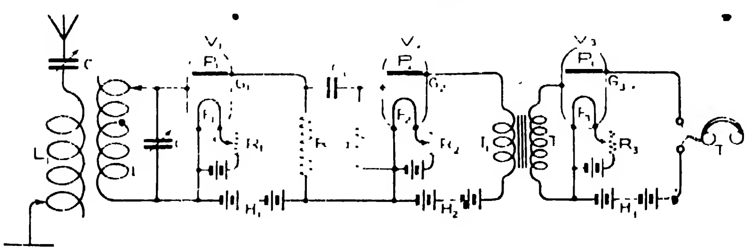


FIG. 195.—A combined resistance H.F. amplifier, detector, and L.F. amplifier.

amplifier; the second as a rectifier, and the last as a low-frequency amplifier.

Fig. 196 shows this circuit in practical form. It has the advantage of being suitable for receiving weak signals and yet being without troublesome tuned intermediary circuits. It is

therefore very suitable for general interception work where it is desired to change rapidly from one wave-length to another.

Connecting-up Circuits.—The reader is again reminded that instead of arranging all these various circuits as shown, it is usually preferable to have, say, a three-valve low-frequency amplifier which may be connected rapidly to any circuit. This latter circuit may be varied as much as possible without alteration to the low-frequency amplifier which can always, be connected to any circuit. Both the experimental circuit and the low-frequency amplifier may have the filaments of their valves heated by the same accumulator, and the same anode battery may be employed if no circuits in either case came between this battery and the filament battery.

Fig. 197 is an example of the method recommended. It

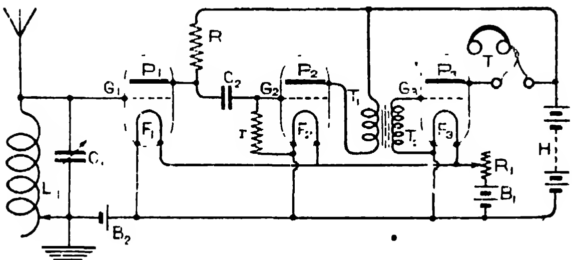


FIG. 196.—Practical form of Fig. 195 circuit.

shows a separate three-valve L.F. amplifier connected to a high-frequency amplifier possessing tuned inter-valve oscillatory circuits. The letter A represents the experimental circuit and B the low-frequency amplifier. A frame aerial L is shown. The anode battery H_1 may be used if desired for the B circuit as well as the A circuit.

Fig. 198 is an example of a radio-frequency amplifier followed by a detector amplifier of the type which has a rectifying valve followed by one or two L.F. amplifying valves. The circuit is really still the same as Fig. 197, but has been divided into two separate types of amplifier. The battery H_2 might be left out and the dotted line connection made.

A Combined Two-valve Amplifier.—One of the most useful types consists of a two-valve amplifier, the first valve of which may be used as a detector if desired (Fig. 199). Three input terminals X, Y, Z are shown. The last two are the low-

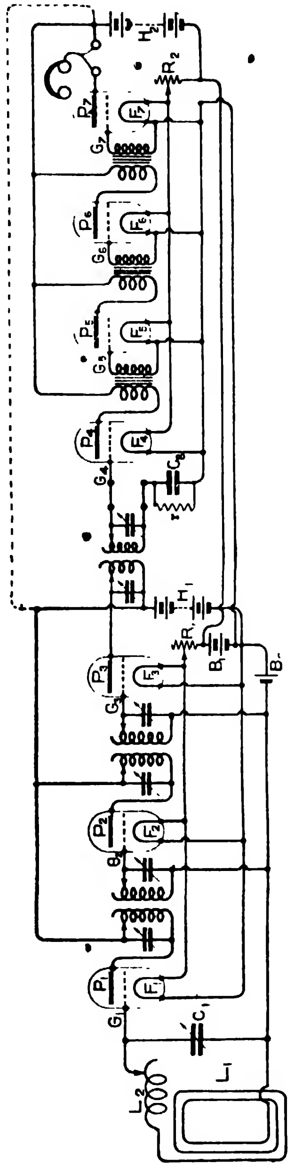


FIG. 198.—Oscillation amplifier followed by a detector-amplifier.

frequency amplifier terminals. Connection is made to X and Z when it is desired to use the arrangement as a low-frequency

detector amplifier. The step-up transformer T_1T_2 is only brought into operation when the two valves are used as low-frequency amplifiers. When the terminals X and Z are used, the transformer is cut out of the circuit.

A two-way switch S is provided, which is placed on the stud D when the terminals X and Z are used. This brings into operation the leaky grid condenser C, which makes the first

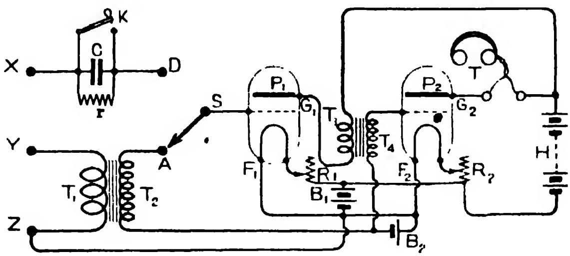


FIG. 199.—A two-valve circuit for use as a L.F. amplifier or detector-amplifier.

valve act as a detector. This leaky grid condenser may for certain purposes be shorted by a switch K. The switch S is moved to A when the terminals Y and Z are used. The secondary T_2 of the step-up transformer T_1T_2 is now connected across the grid and filament of the first valve. Both tubes

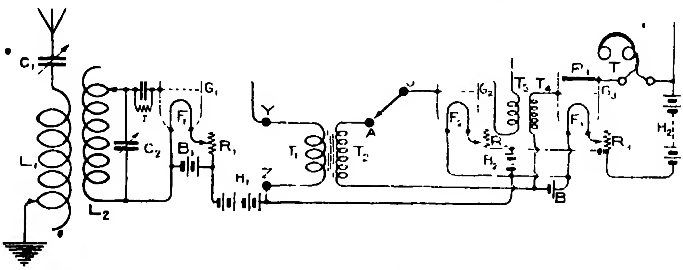


FIG. 200.—Showing the use of the L.F. circuits of a combined amplifier for amplifying rectified currents obtained from an experimental circuit.

now act as low-frequency amplifiers, a small cell B_2 giving their grids a negative potential.

The temperature of the filaments, as shown comparatively by their brightness, is varied by means of rheostats R_1 and R_2. The latter can generally be omitted, but the filament current of a valve to be used as a detector should preferably be variable.

A connection is taken from Z to the filament. This steadies the action of the amplifier and enables us to use three terminals.

Examples of Use of Combined Amplifiers.—Fig. 200 shows a circuit in which the amplifier is connected to act as an amplifier of the rectified pulses obtained in the anode circuit of a valve. On some circuits there may already be a telephone transformer in use, in which case the terminals Y and Z are connected to the telephone terminals of the transformer. The rectified pulses are now twice transformed and a loss of signal strength is thereby incurred. It is preferable to use the connections of Fig. 200.*

Fig. 201 shows the amplifier being used as a detector-amplifier. The step-up transformer is now out of circuit. The terminals used and the position of S should be noted.

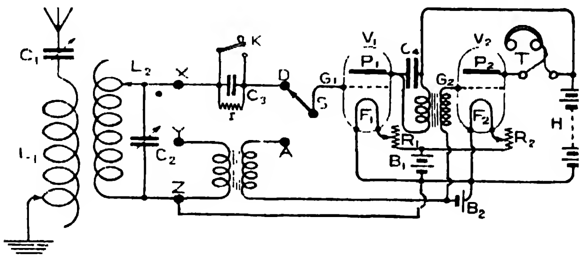


FIG. 201.—Example of the use of the detector circuits of a combined amplifier. The terminals X, Z, are connected across the circuit in which oscillations are flowing.

Below is a summary of the uses of the amplifier and the correct connections to make :—

Terminals X, Z. Switch S at D. Switch K open.

(1) Used as detector amplifier. X and Z may be connected across any oscillatory circuit.

(2) X and Z may be connected across the resistance of a resistance oscillation amplifier.

Terminals X, Z. Switch S at D. Switch K closed.

(1) Used as a low-frequency amplifier without a step-up transformer. X and Z may be connected across the telephone condenser of a crystal detector receiving circuit.

(2) X and Z may be connected across the resistance of a resistance detector amplifier, provided there are rectified currents passing through the resistance.

* In this arrangement separate batteries are necessary. This is a disadvantage of the amplifier of Fig. 199. Four terminals are preferable.

(3) X and Z may be connected across the telephone terminals of a circuit already employing a telephone transformer. If this transformer is of the step-down type, as it usually is, the arrangement is not very efficient.

(4) X and Z may be connected across any circuit in which low-frequency current variations are taking place.

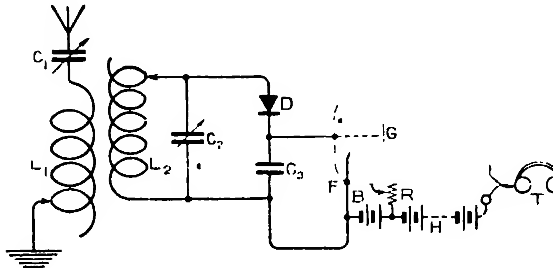


FIG. 202.—Vacuum tube used as an amplifier of the rectified pulses from a crystal detector

Terminals Y, Z. Switch at A. Switch K closed or open.

(1) Used as a low-frequency amplifier with step-up input transformer. Y and Z may be connected across the telephone condenser of a crystal detector receiving circuit.

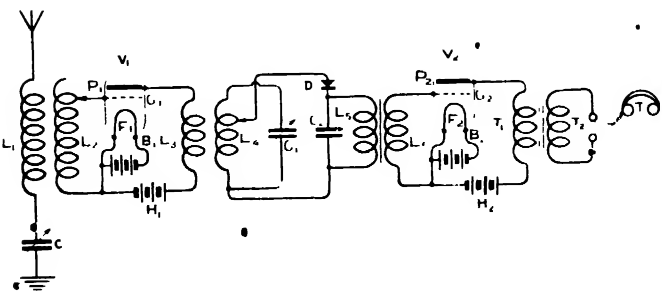


FIG 203.—Use of vacuum tubes with crystal detector.

(2) Y and Z may be connected in place of the telephones in the anode circuit of a vacuum tube used as a detector.

(3) To Y and Z may be connected any circuit in which flow current variations which are to be amplified.

Three-valve Amplifiers.—It will be readily seen that instead of two valves, three may be used without altering the general arrangement.

Use of Crystals in Conjunction with Amplifiers.—Crystal detectors may be used in any part of a circuit where a detecting valve would normally be used. Fig. 202 shows a very simple circuit where the valve is used as an amplifier. Instead of one valve we could use several in the form of an amplifier.

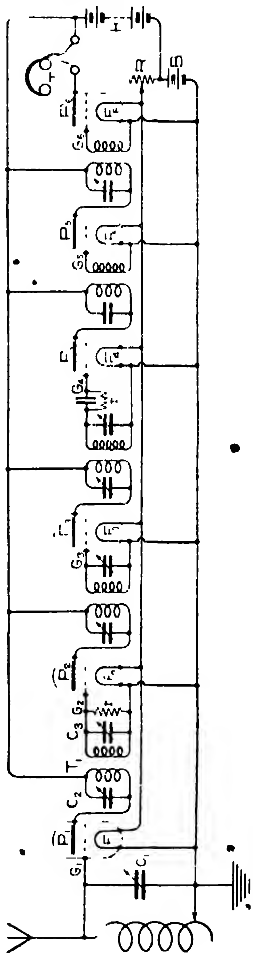


Fig. 203 shows a circuit in which the first valve acts as an amplifier of incoming oscillations. A radio-frequency transformer L_3L_4 passes the amplified oscillations on to a detector circuit containing a crystal detector D. The rectified pulses are then passed on by means of a step-up transformer to the second valve V_2, which is used as a low-frequency amplifier. In the anode circuit of the second valve is a transformer T_1T_2, followed by a pair of 'phones T or some other indicator. This circuit is given by the Ges. für Drahtlose Telegraphie in British Patent 8824/13 (April 15/13). It is stated that the radio-frequency transformer L_3L_4 may be dispensed with, the detector D being placed directly in the high-frequency circuit.

Two French Combined Amplifiers.—Fig. 204 shows a type of amplifier which has been developed by Marius Latour.* The first three valves act as high-frequency amplifiers. Although iron-core transformers are used, very good results have been obtained, both primary and secondary windings being tuned to the incoming wave-length. The

* See British Patent, 130012 (Nov. 30/16).

third valve acts as a detector and the remaining three as low frequency amplifiers of the rectified current. This circuit was designed for the reception of long waves. To prevent this class of circuit from oscillating of its own accord a resistance R may be connected across the grid and filament of the second valve as shown. Other methods have previously been described.

Fig 205 shows rather a complex amplifier developed by Marius Latour.* It consists of four valves, the first three of which act as high-frequency amplifiers, the valves being coupled together by transformers T_1T_2, T_3T_4. and T_5T_6. which are designed for a limited range of wave-length. The fourth

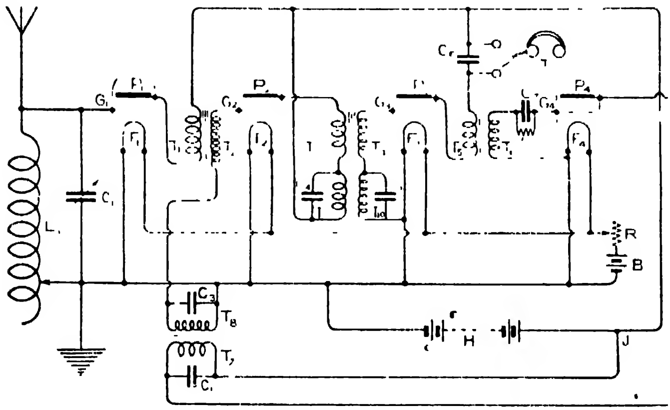


FIG. 205.—Four-valve H.F amplifier in which the rectified pulses are led back from the last valve and amplified by the system.

valve acts as a detector, the rectified current being now led from P_4 through the primary T_7 of a step-up transformer T_7T_8 and thence to the anode battery H and the filament. The secondary winding T_8 of the transformer T_7T_8 is included in the grid circuit of the second valve, which consequently amplifies the low-frequency pulses at the same time as the high-frequency oscillations. These latter, however, do not pass through T_8 but through the shunted condenser C_3. The low-frequency pulses are amplified by the second valve and pass through the primary winding T_9 of a step-up transformer T_9T_{10}, the secondary T_{10} of which is in the grid circuit of the third valve. This valve also magnifies the low-frequency

* See British Patents, 131092 (April 30/17) and 132668 (Nov 17/17)

pulses which now influence the telephones T included in the anode circuit of the third valve. Fixed condensers are connected across T_8, T_9, T_{10}, and T in order that these windings shall not affect the high-frequency oscillations flowing simultaneously in the same circuits.

This circuit would appear to be highly sensitive. It is not, however, as sensitive as might be supposed, and the range of wave-lengths it can receive is very limited. This is due to the natural wave-length of the high-frequency iron-core transformers T_1T_2, T_3T_4, and T_5T_6. Circuits of this type may be arranged so that oscillation transformers replace the iron-core transformers which are used to pass on the H.F. currents.

CHAPTER IX.

MULTI-STAGE RETROACTIVE RECEIVING CIRCUITS.

WE now come to a series of circuits employing more than one vacuum tube and which utilise the phenomenon of retroactive or regenerative amplification.

A Two-valve Retroactive Circuit.—Fig. 206 shows how a two-valve circuit employing retroaction may be arranged.

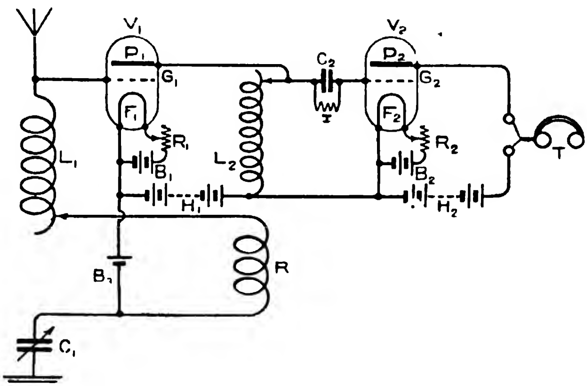


FIG. 206.—Simple two-valve retroactive circuit

A portion R of the aerial inductance is coupled to the inductance L_2 which, in the figure, is shown aperiodic. Retroaction is thus obtained and the magnified oscillations are then applied to a second vacuum tube V_2, which is arranged to act as a detector. If the range of wave-lengths to be received is wide, the inductance L_2 should be variable in steps. If desired, the circuit may be tuned by the addition of a variable condenser across L_2; although rather more efficient, this arrangement will require careful tuning.

Practical Two-valve Retroactive Circuit.—Fig. 207 shows a

very useful retroactive circuit in which only one anode battery and one filament-heating accumulator is used. Its principle is similar to that of Fig. 206. It is especially suitable for receiving long waves since the use of a small retroactor coil R is more convenient for coupling purposes than the large inductance L_2. For short waves, however, the coil L_2 can be coupled to L_3 and the small separate coil R eliminated. The anode oscillatory circuit L_3C_3 is shown tuned.

The second valve is connected in the usual way as a detector. If it is not desired to have a separate aerial circuit L_1C_1, the aerial and earth connections may be made to the grid oscillatory circuit as shown by the dotted lines.

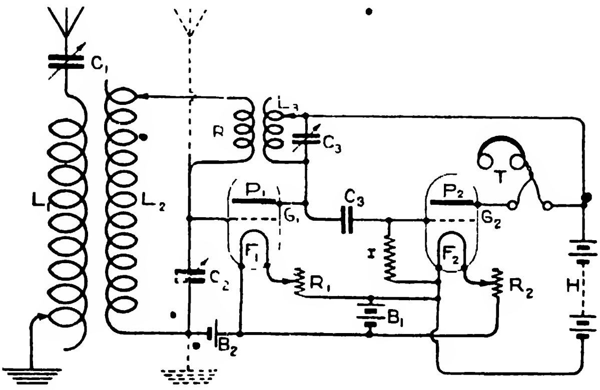


FIG 207.—Practical two-valve retroactive receiver.

This class of circuit is to be highly recommended as a receiver of damped waves. It may also be used as a receiver of continuous waves as will be explained later.

Method of Tuning Fig. 207 Circuit.—The best method of tuning a circuit of the Fig. 207 circuit is as follows: Tighten the coupling between L_1 and L_2. Loosen that between R and L_3. Disconnect one side of C_3 (a switch may be provided) or adjust it to the minimum capacity: adjust L_3 to a low value; the anode oscillatory circuit will now be aperiodic. Tune L_1C_1 and L_2C_2 until the loudest signals are heard in T. Now tune the circuit L_3C_3. Tighten the coupling between R and L_3 to cause retroactive amplification. Loosen coupling of L_1 and L_2 to eliminate interference. Retune all circuits slightly to give maximum strength of signals.

Retroaction between Second and First Valves.—In the last figure we saw how the anode oscillatory circuit of the first valve acted in a retroactive manner on the grid oscillatory circuit of the same valve. This arrangement is not necessary.

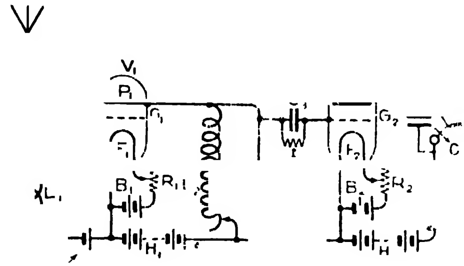


FIG. 208.—Two-valve circuit in which retroaction is obtained in the second vacuum tube.

We can, if we desire to do so, couple the inductance L_3 (Fig. 207) to the inductance L_1.* Or we can use the arrangement of Fig. 208, in which an inductance coil is included in the anode

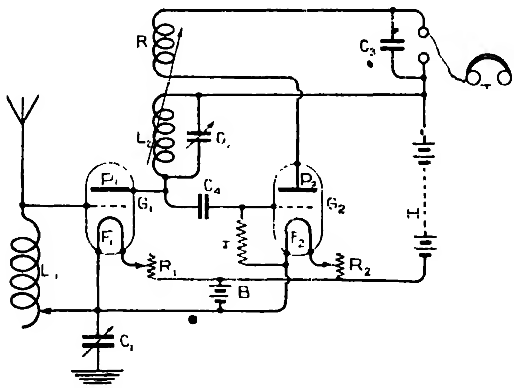


FIG. 209.—Practical two-valve receiving circuit employing retroaction.

circuit of the second valve. This circuit may conveniently be aperiodic and consists of the retroactor coil R coupled to L_2.

Since this circuit is of considerable value and is, if anything,

* Since L_1 is coupled to L_2 we have simply used L_1 as an intermediary circuit.

preferable to the circuit of Fig. 207, it is rearranged in a practical manner and shown in Fig. 209. The reader will have had such experience of this method of practical rearrangement that an explanation of the circuit is unnecessary.

The retroactor coil R might, if desired, be coupled to the aerial tuning inductance L_1, although this is not recommended. By remembering the general principles of retroaction, the reader will see that the "sense" of the retroactor coil will not be the same when coupled to different circuits to obtain retroaction. For example, the coil R might have to be reversed (or its connections reversed) in order to retroact properly on the coil L_1. The E.M.F.'s induced by the retroactor coil should always be in phase with the existing E.M.F.'s. It should be remembered, in this connection, that the high-frequency potentials of the anodes in an auto-coupled series of vacuum tubes vary alternately in sign. Thus, in an amplifier when the grid of the first valve is positive, the anode will be negative; consequently the grid of the second valve will be negative and the anode of the second valve positive.* If, then, we wanted to use retroaction we would have to do it in such a way that the induced E.M.F. made the grid of the first valve positive. It would then reinforce the existing positive potential on the grid at that moment and retroactive amplification would be obtained. This principle applies in all retroactive circuits. Many experimental circuits fail because the retroaction is in the reverse direction and tends to damp out the incoming oscillations. In some circuits which tend to oscillate of their own accord too readily, reverse retroaction is sometimes employed to counteract this tendency.

Directly-coupled Detector Amplifiers using Retroaction.—The principle of Fig. 208 may be applied to any of the circuits from Fig. 155 to Fig. 168. When several valves are used the retroaction may be obtained in the first valve, in the last valve, in any intermediary valve or between any two valves in the series. It does not appear to make much difference how or where the retroaction is obtained provided it *is* obtained. Many peculiar results are frequently obtained when experimenting with vacuum tube circuits; the operator will perhaps find that by touching a certain part of the circuit much louder

* This is not true of all amplifiers on account of small alterations of phase. The point it is desired to emphasise is that the change of phase alters with each valve

signals are obtained. These effects are almost invariably due to one or other of the different forms of retroaction, and instead of wasting time trying to obtain a permanent artificial effect which has the same result as touching with the hand, it is better to use in the circuit one of the well-known methods of obtaining retroaction. The most generally useful one is that of using a retroactor coil. It has the advantage that the degree of retroaction may be varied smoothly and may also be made to act in a reverse direction.

Retroactive amplification is, of course, limited in the case of damped waves. It can be carried on until the waves of one train are made to die out just before the next wave-train begins. If the degree of retroaction is increased past this point the circuits involved commence to oscillate of their own accord, a phenomenon which is not desired. It is therefore only necessary to obtain retroaction in one vacuum tube. If retroaction is obtained, say, in the first valve of an amplifier-detector and is of such a degree as to cause a train of damped waves to die out just before the arrival of the next train, any subsequent retroaction in any of the following valves will cause the wave-trains to merge into each other with a resulting loss of signal strength.

When continuous waves are being received the same principles do not apply. There are no wave-trains but there is simply a continuous stream of oscillations, all of the same amplitude, lasting as long as the key of the sending station is depressed. There is obviously no question of avoiding running the wave-trains together. The amplification of continuous waves obtained by retroaction is due to the increasing of the amplitude of the oscillations. If, however, retroaction is carried too far, the circuits may oscillate of their own accord and this oscillatory current will interfere with the incoming continuous waves, producing undesirable effects.

Indirectly-coupled Amplifiers using Retroaction.—The various amplifier-detectors from Fig. 155 to Fig. 182 may all be fitted with retroactive couplings. As before, the coupling may be from the anode circuit of one valve to the grid circuit of any of the preceding valves.

Fig. 210 shows an amplifier-detector in which retroaction is obtained in the first valve. In this circuit the anode oscillatory circuits are shown as aperiodic while the grid oscillatory circuits are tuned. In the figure, a portion R of

the anode inductance coil of the first valve is coupled to the inductance L_1. The coupling between the inter-valve oscillatory circuits is variable.

Fig. 210 may, of course, be varied by coupling, say, the last anode inductance coil to the inductance L_1. As the oscillations in the last circuit will be very much stronger than the oscillations in L_1, the number of turns in the retroactor

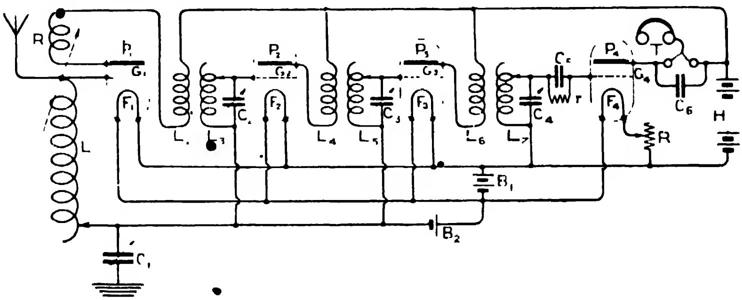


FIG. 210.—Retroactive amplifier with inter-valve oscillation transformers.

coil will not need to be so great (or the coupling may be looser) but the arrangement will be more critical.

Retroaction in Resistance Amplifiers.—Retroaction in this class of amplifier may be obtained in any of the following ways :—

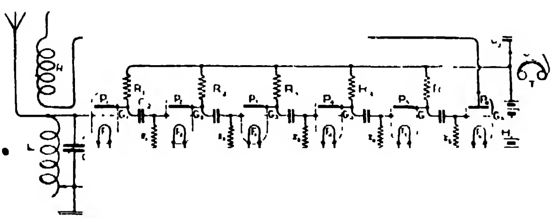


FIG. 211.—A resistance amplifier in which retroaction is obtained by means of a retroactor coil.

(1) The insertion of an aperiodic retroactor coil in the anode circuit of, say, the last valve. This coil would be coupled to the grid oscillatory circuit of the first valve. This arrangement is shown in Fig. 211, which illustrates a six-valve detector-amplifier of very high sensitivity. The advantage of having a retroactor coil is that the degree of retroaction may be varied.

(2) The use of resistance coupling. A resistance of about 10 megohms is connected between the grid of the first valve and the plate of succeeding even valves. Fig. 212 shows a three-valve resistance detector

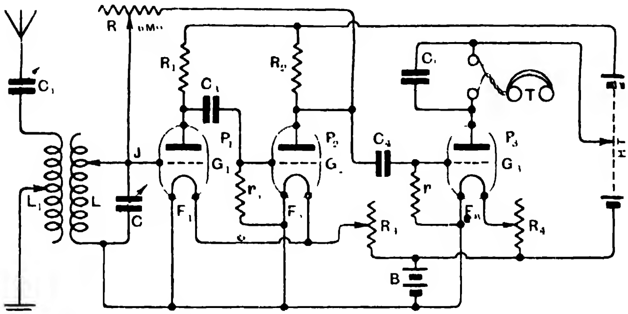


FIG. 212.—Example of the use of a high resistance R to obtain retroaction in a resistance amplifier.

amplifier in which signals are strengthened by the use of a resistance R (which should preferably be variable about an average value of about 6 megohms), which is connected across the anode of the third valve and

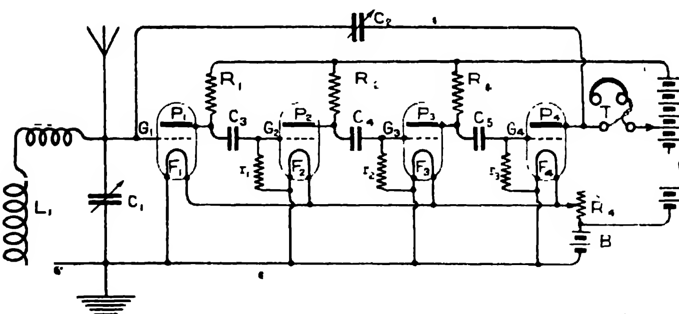


FIG. 213.—Example of the use of a small capacity C_2 to obtain retroaction in a resistance amplifier.

the grid of the first. The disadvantage of this arrangement is that the retroactive coupling cannot be conveniently varied.

(3) The use of capacitative coupling A small variable condenser is connected between the grid of the first

valve and the anode of any of the succeeding even valves. Fig. 213 shows a four-valve resistance detector amplifier in which retroaction is obtained by connecting a small variable condenser C_2 between the grid of the first valve and the anode of the last valve. The inductance L_2 is a loading coil for long waves. The tuning condenser C_1 is shown, this time, in parallel with the aerial tuning inductances. Retroaction, however, is frequently more easily obtained when a condenser, fixed or otherwise, is placed in the earth lead.

By varying C_2 different degrees of retroaction may be obtained and, if desired, the circuits may be made to oscillate of their own accord by increasing sufficiently the capacity of C_2.

(4) A condenser or resistance may be connected across anodes of similar sign.

This arrangement, together with others, is described in British Patent 127014 (Nov. 7/16) by L. N. Brillouin and G. A. Beauvais. The adjustment of the retroaction is more readily obtained with this arrangement. To prevent self-oscillation any of the above methods may be reversed so as to produce "absorption" or reverse retroaction.

Application of above Methods to other Amplifiers.—All the above four methods may be applied to the various types of high-frequency amplifiers and high-frequency detector amplifiers, whether of the directly-coupled, indirectly-coupled, resistance-coupled or impedance-coupled types. It would be an unnecessary elaboration to show examples of their use on all the different kinds of circuits, and this work is left to the reader. Care should be taken, however, in arranging the retroaction to act in an amplifying direction.

CHAPTER X.

The Reception of Continuous Waves.

Effect of Continuous Waves on Crystal Receiver.—We have already seen that signals sent out from a continuous wave transmitting station consist of a steady stream of oscillations of equal amplitude. Fig. 214 shows clearly the differ-

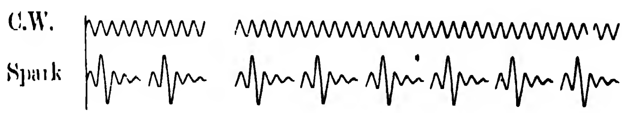


Fig. 214.—The letter "A" as sent by a continuous-wave and a spark station.

ence between the waves emitted from a C.W. (continuous-wave) transmitter and those emitted from a "spark" station. The letter A is being sent. The first line shows how the "dot" and "dash" are composed of a steady stream of oscillations. The second line shows that the dot sent out by a spark station consists of several groups of damped waves. The effect of these two classes of waves on a simple crystal detector receiving circuit is shown in Fig. 215. The continuous stream of

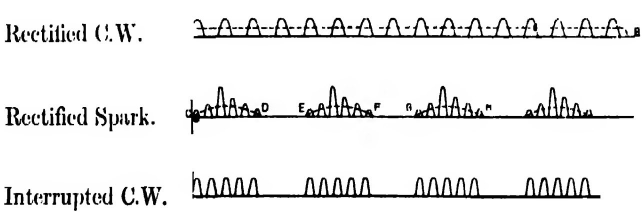


Fig. 215.—Showing the necessity of splitting up continuous waves into groups.

oscillations received from the C.W. station is rectified as shown in the top line. The average result is a steady flow of rectified current through the telephones which commences at the beginning A of the stream and finishes at the end B. If AB

represents a "dash" its effect on a crystal receiver will be to cause a click in the 'phones at the beginning of the stream of oscillations and a click at the end. While the steady current is flowing through the 'phones nothing whatever is heard. These clicks are very noticeable when the receiver is close to a C.W. transmitter and the effect in the 'phones is very similar to the clicking of a sounder. As the receiver is moved further away from the transmitter the clicks become imperceptible.

Now when we are receiving signals from a spark station, we hear a click in the 'phones for each of the wave-trains CD, EF, GH, etc. There is a pulse of direct current (shown by a dotted line) through the 'phones for each individual group of oscillations as it is rectified. For a dash we therefore hear a buzz whose pitch will depend on the number of groups of oscillations per second; in other words, on the spark-frequency of the transmitter. If this group-frequency is 1,000 per second, a clear high note will be heard. We can distinguish many spark stations from each other simply by their note. This cannot be done in the case of C.W. stations.

The obvious way to receive C.W. signals in the form of buzzes is to cut up the steady stream of oscillations into groups at the receiving station. The effect will then be that shown in the bottom line of Fig. 215. Each of these groups will then be rectified and will give a click in the 'phones, a dash being heard as a buzz. The question now arises as to how to cut up the continuous waves into groups.

We could, of course, connect a very rapid make-and-break in the telephone circuit or in the aerial circuit. We would, however, clearly lose half the energy received. In between our groups, the oscillations received would be wasted.

Two forms of interrupters, known as the Tikker and Tone Wheel, have been used for receiving continuous waves, but the advent of the three-electrode vacuum tube has revolutionised the receiving of C.W. signals. The method known as *beat reception* has been developed and is now almost universally used. It not only cuts the continuous waves into groups but also gives a considerable amplifying effect.

To understand the theory of beat reception we require to know the phenomena which take place when two varying currents are flowing in the same circuit.

Interference Effect of Two Sets of Alternations.—Let us suppose first of all that we pass two sets of alternations along

the same wire. What will be the resultant current through that wire? It will depend chiefly on four things:

(1) The amplitudes of the alternations.

(2) The difference in frequency between the two sets of alternations.

(3) The *phase difference* between the two sets of alternations.

(4) Their respective wave-forms.

This latter condition may be ignored since we will assume both sets of oscillations to have a sine-curve wave-form.

Alternations of Same Frequency and in Phase.—Let us first suppose that the sets of alternations are of the same frequency and that they both start at the same time; in other words they will be in phase. When one set of alternations causes a current to flow, say, from left to right in the wire the other set will also be causing a current to flow in the same direction at exactly the same moment. The resultant current will clearly be the sum of the individual currents. If each set of alternations causes a current of one ampere to flow in the wire, the total current in the wire will be two amperes. If the amplitude of the current due to one set of alternations is one ampere and the amplitude of the other set is two amperes, the resultant current will be three amperes. This condition of affairs is shown in Fig. 216.

One set of alternations OABCDEFGH has an amplitude of five amperes. Another set OJBKDLFMH, of the same frequency and in phase with the other set, has an amplitude of ten amperes. The resulting current will be an alternating one of the same frequency as that of the individual currents and having an amplitude equal to the sum of the individual amplitudes. We can construct the resulting current curve graphically by drawing a series of vertical lines *xabc* at various points. Measure the distance *ax*. This will represent the amplitude of the five-ampere set of alternations at that moment. Then measure the distance *bx*. This represents the amplitude of the stronger alternations. Now add *ax* and *bx* together and plot the result as the distance *cx*.

By joining together a number of points *c* found by this means, we will obtain the curve ONBPDQFRH which will represent the resultant current.

Alternations of Same Frequency but out of Phase.—The next case for consideration is when the alternations, though of the same frequency, are out of phase. When the phase

difference is 180° the condition of affairs is that shown in Fig. 217. It will be seen that when one set of alternations is tending to cause a current to flow in one direction the

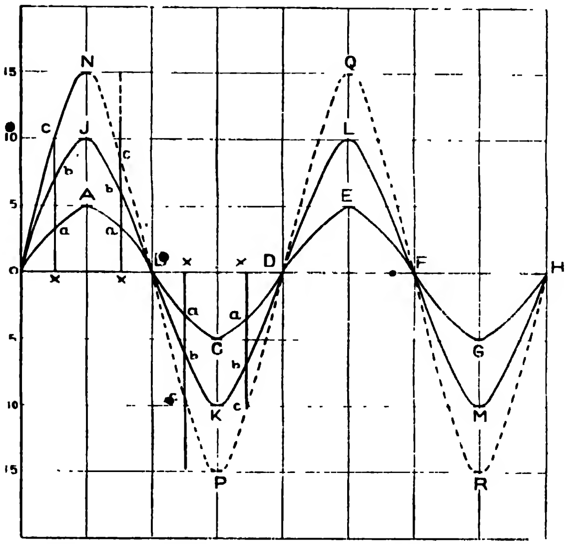


FIG. 216.—Effect of two sets of alternations of same frequency, different amplitude, and in phase.

other set will be tending to produce a current to pass in the opposite direction. The two alternations therefore oppose

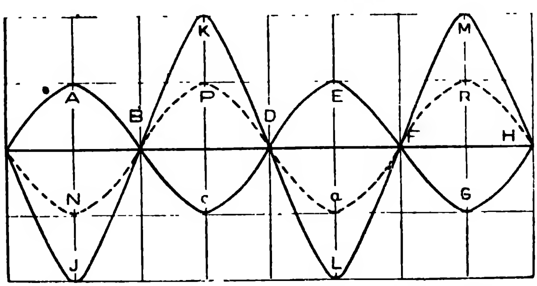


FIG. 217.—Effect of two sets of alternations of same frequency, different amplitude, and 180° phase difference.

each other, and, if they were of the same amplitude, would destroy each other and no current would flow in the circuit. As it is, however, the resulting current is alternating and of

a frequency equal to the original frequency, and its amplitude at any point on its cycle is found as before by taking the *algebraic* sum of the amplitudes of the individual sets of alternations. Thus the amplitude at K is +10 amperes; at C it is −5 amperes; the amplitude of the result alternation at P will therefore be $+10-5=+5$ amperes (point P).

A more general case is that of Fig. 218, which shows the two sets of alternations slightly out of phase. The resultant current is drawn graphically and shown by the dotted line. It will be seen that at certain times (*e.g.* Y and Z) the currents due to the two sets of alternations neutralise each other and

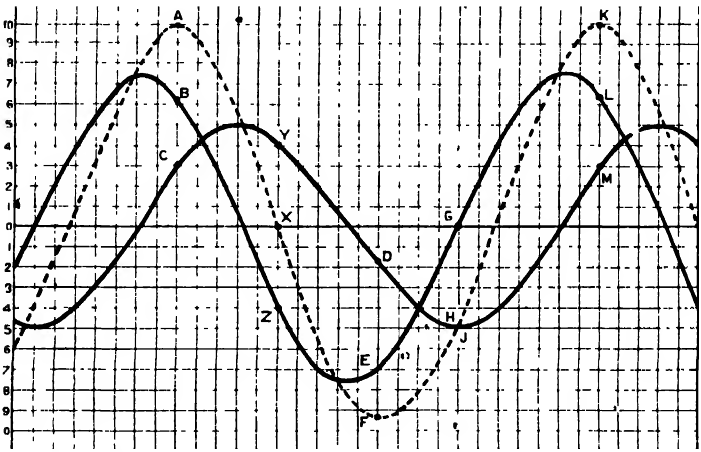


FIG. 218.—Effect of two sets of alternations of same frequency but slightly out of phase and of different amplitude.

cause the resultant current to be zero. At some moments the two currents are helping each other, and at others they oppose each other. It should be noticed, however, that the phase relationship always remains the same and the cycles of the resultant alternating current are of the same amplitude.

Alternations of Different Frequency.– So far we have considered the two sets of alternations to be of the same frequency. If, however, we give one set a slightly different frequency than the other, the phase relationship of the alternations will be continually varying and instead of the resulting current resembling in wave-form the original alternations, we find that its amplitude rises and falls periodically. Fig. 219

shows the result of drawing the two sets of alternations and adding their amplitudes together at numerous points.

The top line shows one set of alternations; the second line shows the other set of slightly different frequency but, this time, of the same amplitude; the third line shows the nature of the resultant current. The reader who is a student should not fail to draw out for himself two such sets of alternations and construct graphically the curve of the resultant current.

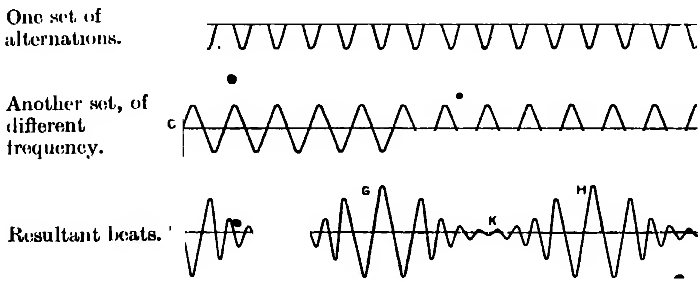


FIG. 219.—Effect of two sets of alternations of same amplitude but different frequency.

The following facts will be noticed concerning the resultant current:—

(1) It is of an alternating nature. Its frequency lies between that of the component frequencies.
(2) Its amplitude rises to a maximum at regular intervals G, H, etc., and in between falls to zero, *e.g.* at J and K.
(3) These maximum points where the two currents assist each other are known as "beats."
(4) The frequency of the beats is equal to the difference in frequency between the two sets of alternations. Thus, if one set had a frequency of 200 and the other a frequency of 260, the number of beats formed per second would be 60.
(5) The amplitude of the beats is the sum of the two individual amplitudes.

Theory of Beat Reception.—What applies to alternations in the above remarks also applies to continuous oscillations, and we have here an exceedingly useful method of cutting the received oscillations into groups.

Fig. 220 shows a theoretical arrangement of an ordinary crystal receiving circuit, to the inductance L of which is coupled a small coil R, through which is passing a continuous oscillating current. This coil will induce oscillations of the same frequency in L, and we will assume that this induced frequency may be varied at will by adjusting the source A of the oscillations. This source may be a high-frequency alternator, an oscillating arc or an oscillating vacuum tube circuit; the last is actually used in practice.

Now let us suppose that the crystal receiving circuit is tuned to incoming continuous wave signals having a length of 600 metres. This wave-length corresponds to a frequency of 300,000,000 (the speed of electric waves in metres per second) divided by 600, which equals 500,000. The frequency of the continuous oscillations in L is therefore 500,000. When these are rectified by the detector D only clicks will be heard in the telephones or, more probably, nothing at all.* If, however, we induce into L continuous oscillations having a frequency of, say, 501,000, these induced oscillations will combine with the existing oscillations to produce beats of a frequency of 1,000 (501,000 minus 500,000) per second. These beats will now be rectified by the detector and a click in the 'phones will be heard for each beat. The beats resemble somewhat in form the signals which would be received from a spark station sending with a spark frequency of 1,000, except that there are more oscillations to each group.

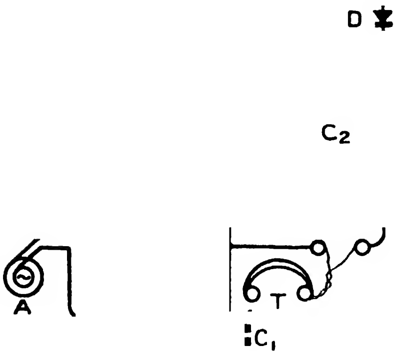


FIG. 220.—Theoretical circuit for beat reception.

Varying the Note of C.W. Signals.—It will be noticed that the pitch of the signals can be varied at will by altering the frequency of the local oscillations induced in L. If we made

* In the case of stations emitting impure continuous waves, the signals heard resemble spark signals.

this local frequency 500,500, the note heard in the 'phones (which has a frequency equal to that of the beats) will have a pitch corresponding to a frequency of 500, which is the difference between the frequency of the incoming oscillations and that of our locally-generated ones. The note will therefore be lower than before. As we decrease the local frequency and make it approach that of the incoming signals, the note of the C.W. signals will become lower and lower. When the local frequency equals that of the incoming oscillations no note whatever will be heard. We have now the conditions of Fig. 218. The two sets of oscillations may be in or out of phase but, since they are of the same frequency, the resultant current will simply be an oscillating one of uniform amplitude which, when rectified by the detector, will give no note in the 'phones.

If we decrease the local frequency below 500.000, beats will form once more, giving a low note at first in the telephones and then higher ones as the local frequency is decreased still further. When the local frequency is 499,000, the signals heard will have a frequency of 1.000, equal to that obtained when the local frequency was 501,000.

Limit of Audibility.—The human ear is only capable of responding to a certain range of note frequencies. This range has been given as from 30,000 to 40,000. These figures represent the *extreme* limits of audibility. There are notes which can be emitted from organ pipes of so low a pitch as to be inaudible. At the other end of the scale there are some notes (emitted by animals) whose pitch is so high that human beings cannot hear them. The highest note which can be heard by a person depends largely on his age and natural sensitiveness of hearing. It is usually in the neighbourhood of about 14.000. For practical purposes, however, we can assume that the highest *effective* note that can be heard has a frequency of 3,000 per second, and it is proposed to use this figure throughout this volume as indicating the highest limit of audibility. The most useful note is the one given by a frequency of about 1,000. Average telephone receivers respond most efficiently to this frequency, higher frequencies not giving such loud signals.

As we vary the frequency of our local oscillations we obtain different beat frequencies. If the difference between the frequencies of the original and the local oscillations exceeds 3,000 practically nothing will be heard in the 'phones.

Variability of Note Received shown Graphically.- The adjustment of the frequency of the local oscillations requires to be made very carefully. If their frequency differs by more than 3,000 from the original oscillations, beats will still be formed and rectified by the detector, but will produce no sound in the telephones since they will be *supersonic* or above audible frequency.

Fig. 221 shows the note heard in the telephones when continuous waves of 500,000 frequency (600 metres) are received by the employment of local oscillations whose frequency may be varied at will. The horizontal axis OX

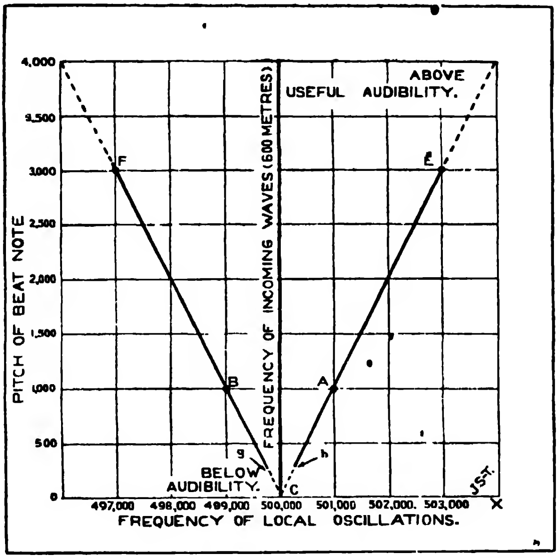


FIG. 221.—Effect of varying the local frequency on the note of the received signals.

shows the local frequency while the vertical axis gives the beat frequency, which is equal to the note frequency. In practice, the frequency of the local oscillations is varied by means of a variable condenser or variometer. The vertical line through C represents the incoming frequency.

If the local frequency is above 503,000 beats will be produced, as shown by the dotted line beyond E, but they will not be audible. At a frequency of 503,000 (at E) we will hear a very high note whose pitch will decrease as we

lessen the local frequency. At 501,000 (A) we will hear a loud high note, ideal for the reception of signals. As the frequency of our local oscillations closely approaches 500,000 no beats are heard and there is a silent interval shown by the dotted line. At 500,000 no beats whatever are formed. Below this figure they are once more formed but do not become audible immediately. Soon, however, a low note is heard which rapidly rises in pitch. At 499,000 the pitch is 1,000 as shown at the point B. The signals now heard are identical to those heard at the corresponding point A on the other side of 500,000. When the local oscillations have a frequency below 497,000 the beats produced are once more inaudible beyond F.

The figure just described explains why, when tuning-in to a C.W. transmitter, we may first hear a very high note. As we vary our tuning condenser, the note falls in pitch and dies out at the point C, which in future we will call *the silent point*. As we continue to turn our condenser, the signals reappear; the pitch at first is low but rises to a very high note which finally dies out. When tuning to a C.W. station the signals heard sound rather like the chirp of a bird.

We can summarise the above remarks thus :—

(1) Beats above 3,000 per second are not effectively audible.

(2) The same note may be heard for two different adjustments of the local frequency.

(3) A silent interval is obtained when the frequency of the local oscillations equals that of the incoming oscillations.

(4) The adjustment of the local frequency requires careful attention. The slightest alteration of the local frequency will cause a different note to be heard in the 'phones.

(5) The operator is able to give the C.W. signals any pitch he prefers.

Selectivity of Beat Reception.—The reader will see from the above remarks that beat reception (or *heterodyne* reception, as it is frequently called) is very selective. The slightest inaccuracy in tuning the local oscillations will result in no signals being heard.

Suppose that two continuous wave stations are transmitting at the same time, one on a wave-length of 600 metres

and the other on a wave-length of 605 metres. Suppose we have tuned our local oscillations to a frequency of 501,000 in order to get readable signals from the 600-metre station. What effect will the 605-metre station have on our receiver? The problem is solved by dividing 605 into 300,000,000. This will give us the frequency (namely, 496,000) corresponding to 605 metres. The 605-metre waves will therefore combine with the local oscillations to give beats having a frequency of 5,000 (501,000 minus 496,000). These beats being above the audible limit will give no sound in the telephones. The 605-metre station will therefore cause no interference whatever. Similarly, a station working on a wave-length of 595 metres would cause no interference.

Even when two stations are sending at the same time, on very slightly different wave-lengths they can be read independently by the operator at the receiving station on account of the different beat notes obtained. Thus, if one station sending on 600 metres, gives a beat note of 1,000, an interfering station sending on 599 metres would give a beat note of just under 200. This very low beat note would not prevent the operator from taking down the high-pitched signals from the 600-metre station.

The selectivity of heterodyne reception is especially pronounced in the case of short waves Take the case of a 100-metre wave-length. The frequency is 3,000,000, and waves more than *one-tenth* of a metre to either side of 100 metres would not affect a receiver tuned to receive the 100-metre waves. The result of this selectivity is twofold:

(1) It allows an immense number of C.W. stations to work in a restricted area without causing any interference with each other.

(2) It makes "tuning-in" a very delicate operation. The capacity of the hand, the movement of the operator, and other external agencies will affect the frequency of the local oscillations and, in the case of very short waves, cause a very large change in the beat note heard, thus making the reception of signals absolutely impossible. The reception of waves as long as 1,000 metres is difficult enough, especially for the novice accustomed to the comparatively rough tuning of "spark" signals.

The selectivity of heterodyne reception decreases as the

working wave-length increases. After about 2,000 to 3,000 metres the tuning of continuous waves presents no difficulties and sharp selectivity is no longer a characteristic feature, although the amplification obtained is still very valuable. Let us suppose, for example, that we are receiving from a C.W. station sending on 10,000 metres. This corresponds to a frequency of 30,000. The local frequency, to give a good note, would be about 31,000 (or 29,000). To avoid producing a beat note, the waves of an interfering station would have to have a frequency either above 34,000 or below 28,000. In other words any station sending on a wave-length between 10,700 metres and 8,800 metres would cause interference. By a similar calculation it may be shown that in the case of long waves, small adjustments of the local wave-length hardly affect the note heard.

In order to be able to *heterodyne* the incoming oscillations without any interference from other stations, there should be a clearance of 6,000 on either side of the incoming frequency. For example, three stations working on wave-lengths of 980, 1,000 and 1,020 could not *possibly* interfere with each other.

The Vacuum Tube Oscillator.—Early troubles with beat reception were due to the difficulty of obtaining a convenient source of continuous oscillations. The difficulty of obtaining a steady stream of continuous oscillations has now been effectively solved. The use of a vacuum tube now enables us to generate oscillations whose frequency we can vary in a very simple manner.

Fig. 222 shows an ordinary crystal receiving circuit adapted for use as a receiver of continuous waves. The circuit A is the oscillator. It consists of a retroactive vacuum tube circuit in which continuous oscillations are set up by tightening the coupling between an aperiodic grid circuit inductance R and a tuned anode oscillatory circuit L_1C_1. The circuit, when connected up, will oscillate of its own accord. This phenomenon of self-oscillation is rather remarkable and is usually explained as follows. A momentary accidental E.M.F. on the grid may cause a sudden variation of the anode current. The circuit L_1C_1 consequently tends to oscillate since the condenser C_1 becomes charged and then discharged through L_1. These small oscillations in L_1C_1 induce similar oscillations in R and are thence communicated to the grid of

the vacuum tube. The oscillations are magnified by the amplifying action of the tube and reinforce the oscillations already existing in the circuit L_1C_2, with which they are in phase. The magnified oscillations now induce into R, are remagnified by the tube, and so the process goes on until the oscillations in R and L_1 are self-supporting. This, of course, takes place in the fraction of a second. The frequency of the oscillations thus produced may be varied by altering the value of the variable condenser C_1. This oscillator circuit may be varied in a large number of ways. The condenser C_1 may be connected across R instead of across L_1, in which case the anode circuit becomes aperiodic. Any of the retroactive circuits previously considered may be converted into oscillators simply

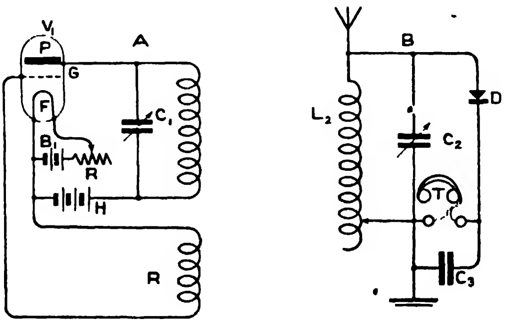


FIG. 222.—Use of a local oscillator, enabling continuous waves to be received with an ordinary detector.

by increasing the retroactive coupling between anode and grid oscillatory circuits, and, of course, dispensing with aerial and earth connections.

The oscillator A induces steady oscillations in the coil L_2 of the receiving circuit and these oscillations form beats with the incoming oscillations. By adjusting the frequency of the local oscillations by means of the variable condenser C_1, a suitable beat note is obtained. By using some kind of oscillator A, any ordinary damped wave receiving circuit may be used to receive C.W. signals. All that is required is to bring the oscillator circuit A close to the inductance L_2 of the receiver.

External Heterodyne C.W. Receiver.—Since the tendency at present is to eliminate the use of crystal detectors, the circuit of Fig. 223 is more likely to be appreciated as a

practical circuit. The detector now consists of a vacuum tube. The oscillator has also been varied, as it is proposed to show examples of different kinds. A single inductance coil AD has a tapping B taken from a point about half-way between A and D. This tapping is taken to one side of the filament (say, the positive side). The portion of the coil A to B constitutes an aperiodic anode circuit while the portion BD shunted by C_1 forms a tuned grid circuit. A switch S is provided which enables the filament current of the oscillator to be switched on or off.

A method of coupling the oscillator to the receiving circuit is that shown in the figure. Instead of having to move the

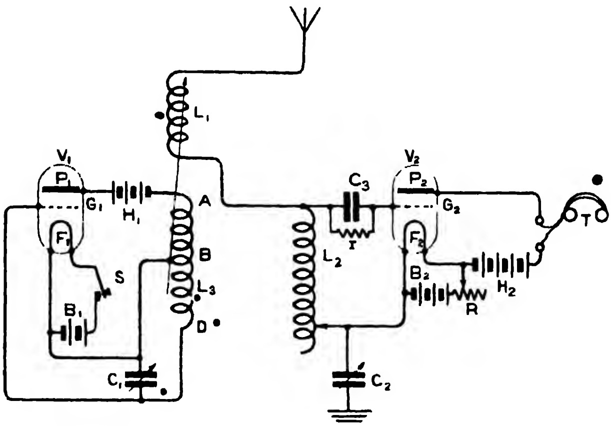


FIG. 223.—External heterodyne circuit with valve as detector

oscillatory circuit bodily so as to induce suitably strong oscillations into L_2, a small coil L_1 may be coupled in a variable manner to the oscillatory circuits of the oscillator. This coil may be conveniently connected in the aerial or earth lead of the receiving circuit. The strength of the local oscillations induced into the receiving circuit may be varied by altering the coupling between the coil L_1 and the oscillator circuits.

The principle of this circuit is applicable to very many of the arrangements which we have discussed in previous chapters. The receiving circuit may consist, for example, of a multivalve amplifier-detector circuit to which is coupled an oscillator circuit to produce beats.

Graphical Representation of Heterodyne Reception.—Fig. 224 shows graphically the various processes which take place when, say, a "dash" is received from a C.W. station. The first line shows the stream of incoming oscillations. The second line shows the oscillations induced in the receiving circuits by the oscillator. The third line shows how the two sets of oscillations come in and out of phase and produce beats at regular intervals. The bottom line shows the beats rectified, by the detector; the positive half-cycles are cut off; this would happen if we adjusted our valve to a point on the upper bend of its anode curve, or employed grid current rectification. The dotted line shows the average pulse of direct current which will pass through the telephone receivers at each beat. In this figure we have shown the local high-frequency current and the incoming oscillations having the same amplitude

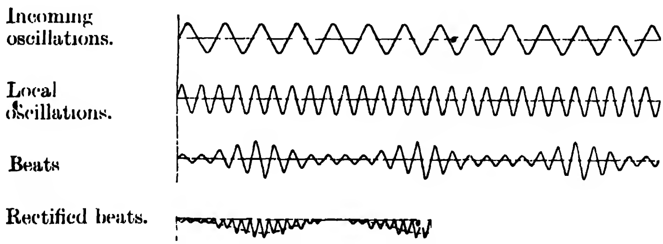


FIG. 224.—Graphical representation of beat reception.

It should be noted that since the two sets of oscillations are continually coming in and out of phase with each other, it makes no difference whether the two streams *start* in phase or not.

The amplification obtainable by means of heterodyne reception will be seen from the figure. The E.M.F. of the beats is *twice* that of the incoming oscillations. Since the telephone current is proportional to the square of the E.M.F. applied to the detector, a signal amplification of four times will thus be obtained.

Effect of Ratio of Local to Incoming Current.—In the above example we have taken the local oscillations to have the same amplitude as the incoming ones. If this amplitude is A, the E.M.F. of the beats will be $2A$. It is to be noted that in between the beats the current becomes zero.

Now let us suppose that the local oscillations are stronger than the incoming ones; suppose their respective amplitudes

are *B* and *A*. The condition of affairs is now that shown in Fig. 225. It will be seen that the amplitude of the beats equals $A+B$. In between the beats, however, the current does not die down to zero; when the two sets of oscillations are directly opposing each other (that is, when they are 180° out of phase) the E.M.F. of the resultant current will be $B-A$ at the "valleys." In the bottom line the mean telephone current never becomes zero. The *effective* E.M.F. of the beats

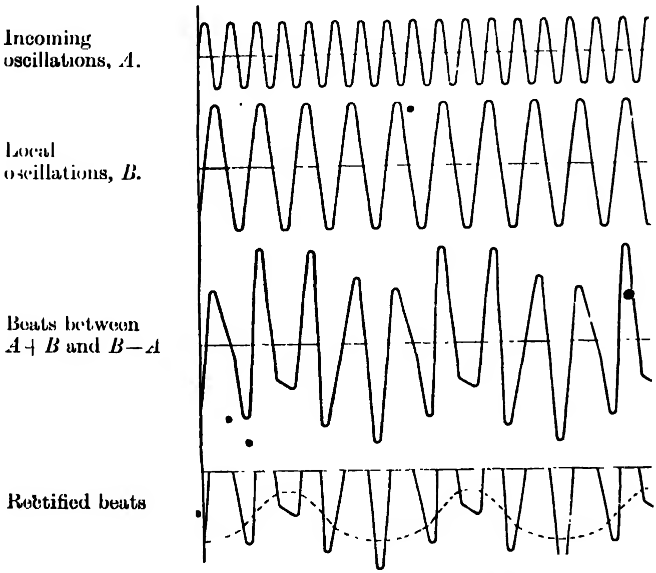


FIG. 225.—Beat reception when the local oscillations are stronger than the incoming oscillations. Signal strength depends on amplitude of incoming oscillations.

will consequently be the rise above the lowest E.M.F.; it will therefore equal the difference between the E.M.F. at the summits and the valleys; actually, this is $(B+A)-(B-A)$, which equals $2A$.

When these conditions exist, the strength of signals will depend on the amplitude of the incoming oscillations. It is therefore necessary to tune the aerial and receiver circuits very carefully to the incoming frequency. Any mistuning will cause a loss of signal strength.

Now let us examine the effect of using a heterodyning current of *less* intensity than that of the incoming oscillations.

The conditions are now those shown in Fig. 226. The amplitude A is now greater than B. The E.M.F. of the beats will be $A+B$. The E.M.F. of the valleys between the beats will equal $A-B$. The *effective* E.M.F. of the beats will therefore be $(A+B)-(A-B)$, which equals $2B$. Thus we see that the strength of signals heard will now depend entirely on the strength of the heterodyning current and not at all on the amplitude of the incoming signals. The effect of this will be:

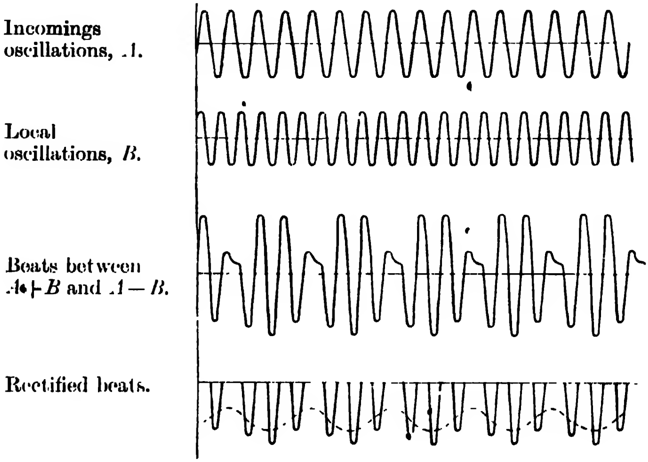


FIG. 226.—Beat reception when the local oscillations are weaker than the incoming oscillations. Signal strength depends on amplitude of local oscillations.

(1) Signals from all C.W. stations will have the same strength if the amplitude of their oscillations is greater than that of the local oscillations.

(2) Even if the aerial circuit or receiving circuit is mistuned, the resultant diminution of the amplitude of incoming oscillations will not affect the strength of signals heard. Consequently accurate tuning will be impossible. Only when we have mistuned to such an extent that we have reduced the amplitude of A to less than that of B will the signal strength begin to decrease. We have now obtained the conditions of Fig. 225.

(3) It is useless amplifying the incoming oscillations before heterodyning them if the heterodyning

current is of less amplitude than the incoming oscillations.

(4) The strength of the signals heard in the telephones may be regulated by varying the strength of the induced local oscillations.

These theoretical deductions are largely borne out in practice. The disadvantages of using a local current of too small an amplitude are very obvious. We are not getting the full efficiency out of our incoming oscillations. We will also experience considerable interference through being unable to tune our circuits correctly. When our local oscillations have the same strength as the incoming ones we get the full benefit of the latter. Tuning is accurate and the signals are much louder. We are also not interfered with very much by high-powered C.W. stations. However strong the oscillations from the latter may be, the E.M.F. of the beats produced will only be twice the amplitude of the local oscillations. The signals from the interfering station can therefore be no louder than those of the station from which we desire to receive. If, however, we make our local oscillations much stronger than the oscillations we desire to detect, although our desired signals are not altered very much, yet those from the higher-powered interfering station will be very greatly increased and may completely drown the desired signals. In practice, therefore, when interference from a high-powered C.W. station is experienced it may frequently be lessened by decreasing the amplitude of the local oscillations.

Opinion of Armstrong and Others.—E. H. Armstrong has contributed an interesting paper on heterodyne amplification to the Institute of Radio Engineers.* His observations indicate that the best results are obtained when the local current is in excess of the incoming current. He found that when weak oscillations were being received the local oscillations had to be made very much stronger than the original ones to obtain the best results, and that the signals thus obtained were very much louder than those obtained when the heterodyning current equalled the incoming current. In the case of strong oscillations, the advantage of using a local current of higher amplitude was not so marked. The results he obtained were illustrated graphically. It was seen that in

* E. H. Armstrong, "A Study of Heterodyne Amplification by the Electron Relay," *Proc. I.R.E.*, **5**, 2, 145 (April, 1917).

each case there is a certain strength of local oscillations which gives the best results (which Armstrong calls "optimum heterodyne").

The explanation of this phenomenon seems to lie in the fact that the sensitiveness of the detector is improved by the local oscillations and that there would be no advantage in increasing the local current beyond the value of the incoming oscillations if it were not for this complication. The function of the local current is primarily to produce beats; its secondary effect seems to be to bring the operating point on the characteristic curves of the detecting valve to the most suitable position.

C. Ort * suggests that the local oscillations have a polarising effect on the detector and increase its efficiency. He states that every detector with a rectifying characteristic can be polarised in this way by applying a sustained radio-frequency voltage to its terminals. The resultant amplification is independent of the production of beats. It is noticeable when spark stations are being received and when the local oscillations have the same frequency as incoming continuous waves, the signals in the latter case being detected by an Einthoven string galvanometer.

There is very considerable variance of opinion as to the degree of amplification obtainable by the heterodyne method. Some state, like B. Liebowitz,† that the maximum true amplification due to the heterodyne is four; that this is obtained when the local current is equal in amplitude to the signalling current, and that any further increase in response which may be obtained by an increase in the local current is due to an improvement in the efficiency of the receiving apparatus. This statement has been opposed by L. Cohen,‡ who considers that the amplification obtainable is unlimited. Marius Latour § and J. L. Hogan, Jun., have contributed their opinions on the subject. G. W. O. Howe has also discussed the subject in a very interesting manner in the *Proceedings of the Institute of Radio Engineers* for October, 1918 (vol. **6**, 5, 275). In view of the existing controversies, the reader should consult the references given.

* C. Ort, *Proc. I.R.E.*, **5**, 2, 163 (April, 1917).

† B. Liebowitz, *Proc. I.R.E.*, vol. 3, page 185, June, 1915.

‡ L. Cohen, *Proc. I.R.E.*, July, 1913; June, 1915.

§ M. Latour, *Electrical World*, April 24, 1915 J. L. Hogan. *Proc. I.R.E.*, July, 1913.

It is, however, certain that the amplitude of the local current should be variable and should be adjusted to give the loudest response in the telephone receivers. Moreover, for weak signals it is preferable to employ stronger local oscillations.

Tuning to C.W. Signals.—The use of an external oscillator makes it a little difficult to pick up C.W. stations rapidly. Two circuits have to be tuned: the receiving circuit and the oscillator. The oscillator should be calibrated in wave-lengths or possess a chart showing the wave-lengths corresponding to different adjustments of the variable condenser. If it is desired to receive signals whose known wave-length is, say, 8,000 metres, the oscillator is set to a wave-length a little to one side or other of this value; the receiving circuit is now tuned until the signals are heard. The best beat note may now be obtained by a slight readjustment of the oscillator. This method is not suitable for tuning-in to short waves since it is impossible to set the oscillator to the correct value. If the wave-length to be received is 1,000 metres, the oscillator is set to this value and the oscillator condenser turned backwards and forwards on either side of this wave-length while adjustments are made on the receiving circuit until the station required is heard.

It is interesting to note the effect of mistuning the receiver circuit. If the oscillator be set to give a suitable beat note with the incoming oscillations, mistuning of the receiver circuit will only result in weaker signals and will not cause any alteration in the *pitch* of the note heard. This is because the frequency of the incoming oscillations is not affected by mistuning; even if the receiver circuit is a little out of tune, the incoming oscillations will force themselves into the circuit, but their amplitude will be decreased. If the circuit is mistuned to too great an extent the oscillations will be unable to force themselves into it and no signals will be heard. This explains why when tuning-in to C.W. signals the note heard is at first weak and then reaches its maximum loudness when the receiver is correctly tuned and then dies off again as the tuning is altered. The pitch of the note heard will not, however, have altered. Its value depends *solely* on the frequency of the heterodyning oscillations and not at all on the receiving circuit.

Arco and Meissner's External Heterodyne Receiver.—In British Patent 252 (Jan. 5/14), Arco and Meissner describe

what is in effect an external heterodyne circuit for receiving continuous waves. It is shown in Fig. 227. The vacuum tube to the right generates oscillations of a frequency slightly different to that of the incoming waves. These local oscillations pass through L_7 and induce into the inductance of the detector circuit which is also coupled to the closed receiving circuit. The resultant beats are rectified by the detector D.

Radio Frequency Amplification of C.W. Signals.—Incoming continuous waves may be amplified in exactly the same way as

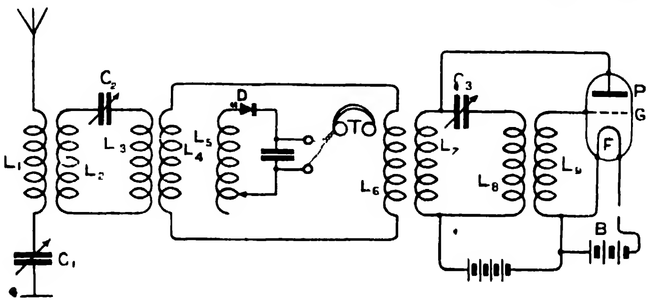


FIG. 227.—An Arco and Meissner heterodyne circuit.

damped waves. One or more vacuum tubes may be connected in cascade for this purpose. Any of the circuits of Chapter VI. may be used with an external heterodyning oscillator.

Fig. 228 shows a very useful kind of 2-valve receiver circuit. It is practically Fig. 160 with the addition of an oscillator. Incoming oscillations are amplified by the first vacuum tube in the anode oscillatory circuit of which they are heterodyned by the oscillator. The beats are rectified by the second valve. The filament current of the first valve is shown fixed. The anode voltage of the second valve may be varied separately. This is done merely to show the reader what variations are possible.

The design of the oscillator has also been modified to illustrate another type of arrangement. A tapping A is taken from the middle of the coil L_4 to the filament. The oscillatory circuit is now L_4C_3, and a tapping is so taken that the grid potentials are in such phase as to produce self-oscillation. No retroactor coil is needed with this circuit. The condenser C_3 does not only vary the wave-length of the feeble waves emitted by the oscillator but also varies their

amplitude considerably. It is preferable to use an oscillator in which the oscillations have the same or nearly the same amplitude for different frequencies.

In this figure we have taken a small portion L_3 of the oscillator circuit and coupled it to the coil L_2. The few turns L_3 may conveniently be connected to the oscillator by a foot or two of twin flex. cable. The little coil L_3 may then be coupled to any position of the receiving circuit desired. It might, if desired, be coupled to the inductance L_1, in which case

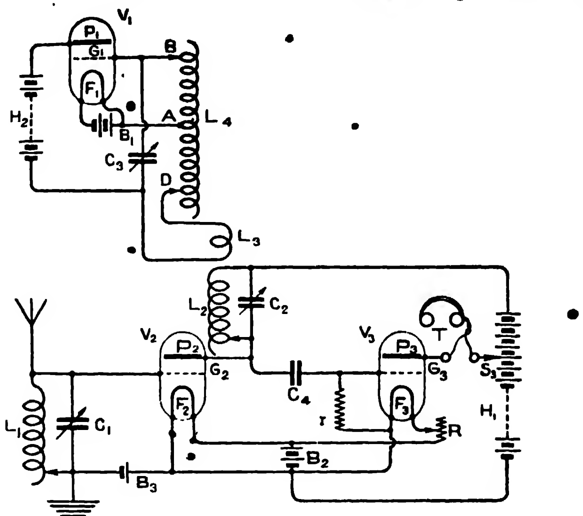


FIG. 228.—Heterodyning amplified continuous oscillations.

the beats would be formed in L_1 and would be amplified by the first valve.

If coupled to L_2 the local oscillation will require to be stronger than if L_3 were coupled to L_1. This is because the incoming oscillations have been magnified in L_2 and we have seen that the ratio of local to signalling current is of importance. The strength of the local oscillations is most conveniently varied up to a certain point by altering the coupling between L_3 and L_2 or L_1. It might also be varied by altering the anode voltage of the oscillator or by providing the latter with a filament current rheostat.

Use of Detector Amplifiers as C.W. Receivers.—In order to avoid filling this volume with unnecessary diagrams, the

author desires to refer the reader to the many detector amplifiers which have been described in previous chapters. *They may one and all be used as very efficient receivers of continuous waves* if an external heterodyning oscillator is provided. The oscillator may be coupled to the aerial circuit or to any of the intermediary circuits if the latter possess inductance coils.

Methods of Coupling Oscillator to Receiver Circuits.—So far we have chiefly considered the oscillator to be a separate instrument indirectly coupled to the receiving circuit. This arrangement is not essential. We could, if we desired, couple the oscillator directly to the receiver circuit; we could use auto, resistance, or capacitative coupling. These methods, however, do not lend themselves to variation and are not as convenient as the ordinary indirect coupling.

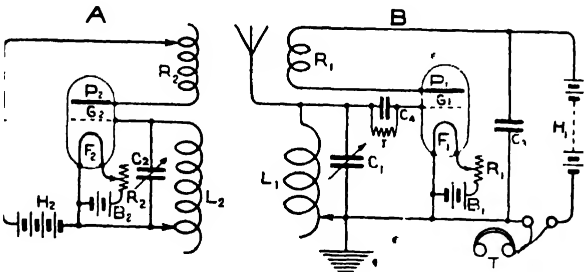


FIG. 229.—Efficient external heterodyne circuit in which the continuous waves are amplified by retroaction.

Retroactive Amplification of Continuous Waves.*—Very good results may be obtained by utilising retroactive effects when receiving continuous waves. Retroaction has not now the effect of lessening the damping but simply increases the amplitude of the incoming undamped oscillations and lessens the resistance of the receiving circuit.

Fig. 229 shows a simple arrangement which is very effective as a receiver of continuous waves. The circuit B is an ordinary retroactive receiving circuit in which retroaction is obtained by coupling an aperiodic anode circuit coil R_1 to the inductance L_1. The A circuit is an oscillator in which the coupling

* See J. Scott-Taggart, "A System for the Reception of Continuous Waves" (a paper read before the Wireless Society of London), *Wireless World*, Jan. 1920; *Electrical Review*, **85**, 2196; *Telegraph and Telephone Age*, Feb. 1, 1920.

between R_2 and L_2 is sufficiently tight to produce self-oscillation. Both R_2 and L_2 are variable in one or two steps in order that the oscillator may be used over a wide range of wave-lengths. The oscillator is placed near the receiving circuit and acts as a heterodyner. The coupling between R_1 and L_1 should be adjusted to give the loudest signals in T. It should not be sufficiently tight to cause self-oscillation in the B circuit.*

Any ordinary retroactive receiving circuit or detector-amplifier employing retroaction may be used to receive continuous waves in this way and the author very strongly recommends the employment of this type of circuit.

Self-heterodyne Circuits.—A very useful type of circuit which is sometimes called the self-heterodyne, endodyne or retrodyne type, is that in which one vacuum tube carries out simultaneously the duties of heterodyner and receiver. Such a circuit is shown in Fig. 230.

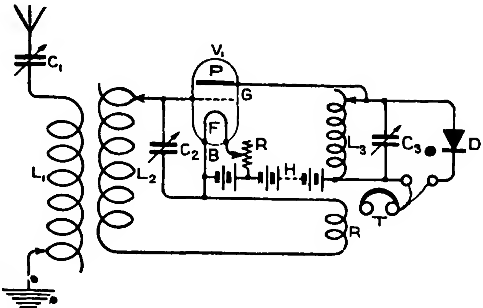


FIG. 230.—Self-heterodyne circuit in which the beats are rectified by a separate detector circuit.

Fig. 230 is really nothing more than an ordinary retroactive circuit in which the retroaction has been increased sufficiently to produce self-oscillation. Let us not think of the aerial circuit L_1C_1 for the moment. The tuned grid oscillatory circuit L_2RC_2 is coupled by means of R to the anode oscillatory circuit L_3C_3. The degree of coupling is increased until continuous oscillations are set up in the circuits. The detector D and 'phones T are connected across L_3 but no signals are heard since the oscillations taking place in L_3C_3 are of constant amplitude. Now let us suppose that continuous oscillations are flowing in the aerial circuit L_1C_1 due to incoming waves. The incoming oscillations

* The filament current and anode voltage for the oscillator may be taken from the receiver batteries in the case of Fig. 229, and in all cases, provided that we arrange that both circuits have the anode battery next to the filament.

induce into L_2 and are heterodyned by the oscillations already taking place in L_2. The beats produced are amplified by the valve and reoccur in the anode oscillatory circuit L_3C_3 and are rectified by the detector D and give audible signals in T.

In this method of reception the valve is made to oscillate at a frequency slightly different to that of the incoming waves. The circuit L_2C_2 is consequently tuned to a frequency slightly different to that of the incoming oscillations which, however, when induced from the aerial circuit, force themselves into the circuit L_2C_2 while maintaining their original frequency. The consequent loss of amplitude is one of the disadvantages of this form of reception.

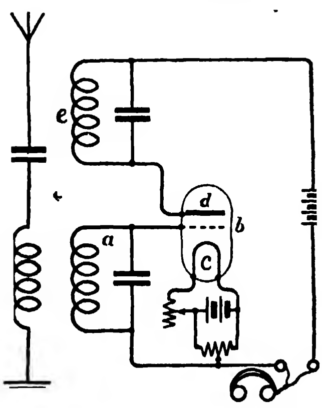


FIG. 231.—"Detectordyne" circuit in which the one vacuum tube carries out simultaneously the functions of heterodyne and detector.

Instead of using a separate detector D the vacuum tube itself may be used to rectify the beats produced. Marconi's Wireless Telegraph Co. and H. J. Round describe in British Patent 28414/13 (Dec. 9/13), a simple arrangement (Fig. 231) whereby one valve carries out the various functions simultaneously. The name detectordyne may be given to this class of circuit. The circuit *e* is coupled to the circuit *a* so that the valve oscillates continuously. The oscillations taking place in *e* are given a frequency slightly different to that of the incoming waves. The incoming oscillations in the aerial circuit induce into the circuit *a*, where they interfere with the local oscillations, producing beats which are then rectified by the valve and detected by the telephones T. The circuit *e* may be arranged to retroact on the aerial circuit if desired.* Another circuit involving the same principles was produced by E. H. Armstrong, and is described in British Patent 24231 (Dec. 18/13). †

Practical C.W. Receiving Circuit.—Fig. 232 shows a simple and effective continuous wave receiver. The coil R is

* The patent only claims apparently the detuning of the circuit *e*.
† The date of this invention is claimed as Jan., 1913, by Armstrong.

aperiodic and is coupled to L_1 sufficiently tightly to cause the vacuum tube to oscillate of its own accord at a frequency which can be varied by the condenser C_1 and the adjustable tapping on the inductance L_1. This frequency is made, as usual, a little different to the incoming frequency. The leaky grid condenser causes the valve to act as a detector.

This circuit is exceedingly simple to tune. To "pick up" a station it is only necessary to vary the condenser C_1, and sometimes the inductance L_1. The frequency of the aerial circuit is varied at the same time as the frequency of the local oscillations. Consequently, the aerial circuit is always a little out of tune when C.W. signals are heard. As the condenser C_1 is moved round, the incoming signals are first heard as a high note which is very faint The frequency at which the valve is now oscillating differs from the incoming frequency by about 10,000. As the condenser is turned round still further, signals become louder and their pitch becomes lower until a point is reached when no sound is heard. The local frequency, at this adjustment, is equal to the incoming frequency; the aerial circuit is now correctly tuned to the incoming waves. If we gradually turn the condenser round still more, signals reappear and gradually acquire a higher note, which finally dies out. The following points should be noted in regard to self-heterodyning circuits :—

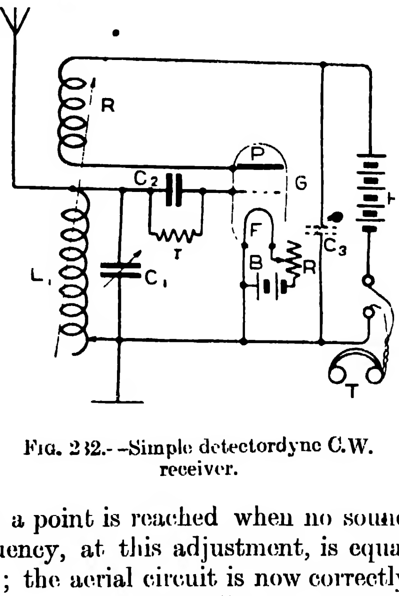


FIG. 232.—Simple detectordyne C.W. receiver.

(1) The receiver is usually slightly mistuned, the incoming oscillations forcing themselves into it. This causes a loss of signal strength.

(2) When receiving waves of less than 2,000 metres length the condenser C_1 which varies the local frequency should be carefully adjusted, otherwise the station may be missed.

(3) The note heard in the telephones may be altered at will by the operator by altering the value of C_1.
(4) The same pitch of note may be heard on either side of the silent interval.
(5) The loudness of the signals heard will depend largely on the value of the anode voltage, filament current, and coupling between R and L_1.

With this class of circuit loss of signal strength results through the mistuning of the receiving circuit. The higher pitched notes are caused by mistuning the circuit a considerable amount.

When, however, a low note is obtained, the receiving circuit is not mistuned to such an extent. This explains why the loudest signals are obtained when the beat note is low. In the case of external heterodyning, the receiving circuit is always in tune with the incoming waves, and the loudest signals usually have a frequency of about 1,000, to which frequency average telephone receivers respond most efficiently.

It is to be noted that the circuit of Fig. 232 may be modified by connecting a variable condenser across R.

Rectification in Self-heterodyne Circuits.—In detectordyne circuits the valve is made to oscillate and also rectify. Now when a valve is oscillating, the anode current is varied about a normal value. The increases and decreases of anode current require to be equal or approximately equal. If we adjust our valve either to the lower bend or the upper bend of the anode current curve the increases and decreases will be widely different and the circuits will not oscillate of their own accord. Self-oscillation will usually only take place when the operating point lies on the steep straight portion of the grid-voltage- anode-current curve.

From this we see that when the same tube is to carry out the two functions of heterodyning and detecting, we cannot obtain rectification by utilising the non-linear characteristics of the anode-current curve. We can, however, use the bend of the grid-current curve while still keeping our operating point on the steep straight portion of the anode curve. Suitable rectification is obtainable by connecting the grid to the negative end of the filament or by the use of a grid condenser. In the case of external heterodyne circuits we can, of course, use any of the methods of detection since the detecting valve does not oscillate.

Radiation from Self-heterodyne Circuits.—Since the vacuum tube of Fig. 232 is oscillating continuously, it is obviously emitting feeble waves which are radiated from the aerial. True, the oscillations are weak, but they are quite sufficient frequently to carry a distance of several miles. The receiving circuit is therefore acting as a very weak transmitter. As such, it will cause very considerable interference to neighbouring receiving stations. Two stations in the same town using circuits of the self-heterodyne type of Fig. 232 may cause endless trouble to each other by overhearing the other station's valve oscillating. If a certain station A is receiving a C.W. station sending on 600 metres his set will be sending out waves of a length just to one side of 600 metres. Another station B, while tuning his set, will hear a note which sounds as if a C.W. transmitting station were keeping his key down. This effect is due to the feeble waves from the receiving station A. When two stations or more are "searching," they will be sending out waves of all lengths and will cause a great deal of mutual interference. It is therefore highly probable that regulations will be made to forbid the use of circuits which radiate while receiving.

Prevention of Radiation from Receiving Circuits.—The type of circuit shown in Fig. 232 is the kind which gives most trouble through radiation. The circuits in which the aerial circuit is loosely coupled to the oscillating valve (as in Fig. 231) do not radiate quite to the same extent. What radiation takes place can be largely minimised by lessening the filament current and anode voltage, which are frequently needlessly high. Unfortunately, most self-oscillating circuits stop oscillating suddenly if an attempt is made to lessen the amplitude of their oscillations. Consequently we find that the local oscillations are frequently unnecessarily strong.

The radiation from an externally heterodyned circuit is usually negligible and gives no trouble. The oscillator, if coupled to a circuit other than the aerial circuit, will not cause radiations from the aerial of any strength. Even if coupled to the aerial circuit the oscillations induced in the latter are not made unnecessarily strong and are usually too weak to interfere with neighbouring stations.

To avoid radiation completely (or almost completely), a circuit similar to that of Fig. 228 may be used. The first valve now acts as a trap allowing incoming oscillations

to be received, but preventing local oscillations induced into L_2 by the oscillator to pass out to the aerial. The self-heterodyne circuit of Fig. 236 also prevents radiation from the aerial.*

Advantages and Disadvantages of Detectordyne Circuits.—The advantages and disadvantages of circuits using one valve as a combined detector, amplifier, and heterodyner, as in Fig. 232, may be summarised as below.

Advantages :

(1) Simplicity. One vacuum tube only is necessary.

(2) Simple tuning. The local frequency is varied at the same time as the tuning of the aerial circuit. The circuit is very suitable for "stand-by" reception.

Disadvantages :

(1) The circuit radiates feeble waves while receiving.

(2) The receiving circuit is always mistuned and loss of signal strength results.

(3) The loudest signals are obtained when the beat note is low.

(4) The amplitude of the local oscillations cannot be smoothly or conveniently varied.

(5) Variation of anode voltage and filament current not only vary the strength of the local oscillations but also the efficiency of the valve as a detector.

(6) Grid current rectification only is possible.

While all self-heterodyne circuits do not possess the disadvantages of the Fig. 232 circuit, yet they all possess some, and the reader will be able to judge them himself. The advantages of external-heterodyne circuits lie in the fact that the above disadvantages are absent in this class of circuit. Moreover an oscillator will be a necessary part of every C.W. receiving station sooner or later. The only real disadvantage of the externally heterodyned circuit is that it is rather difficult to tune rapidly.

Weagant C.W. Receiver.—Fig. 233 shows a circuit which is based on a type of circuit used by Roy A. Weagant. The coil L_3 is coupled to L_4 sufficiently tightly to cause the tube to oscillate of its own accord. The coils L_4 and L_3 may be fixed inductances forming part of the grid and anode oscillatory circuits respectively. This circuit may, like most other

* The author's double-grid valve will receive C.W. without radiating. See British Patent 153681 (Aug. 14/19).

C.W. circuits, be used to receive undamped waves by loosening the coupling between L_3 and L_4 until the valve ceases to oscillate and acts as a combined retroactive amplifier and detector

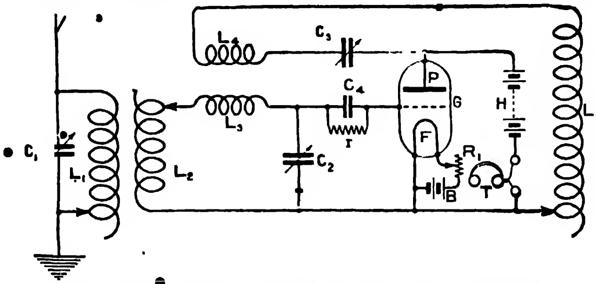


FIG. 233.—A C.W receiver used by R. A Weagant.

Miscellaneous C.W. Receivers.—Fig. 234 shows a collection of circuits which may be used to receive continuous waves. For further information regarding them the reader is advised to turn back to the remarks on Fig. 148 in the

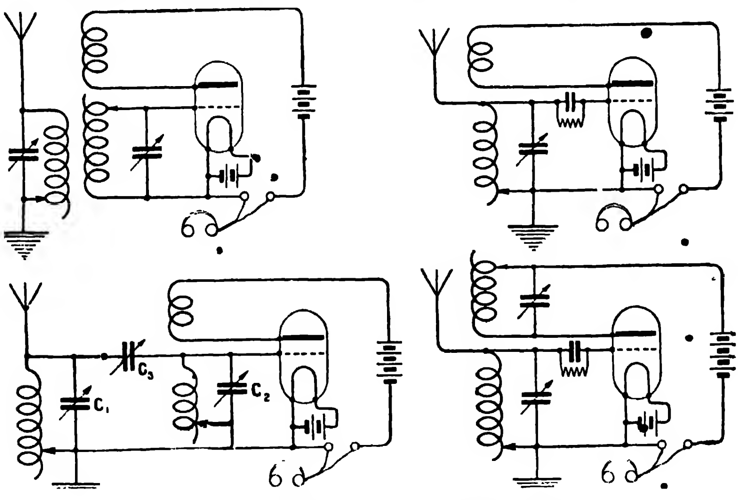


FIG. 234.—Some miscellaneous C.W. receivers.

chapter on retroactive amplification. The reader is again reminded that all retroactive circuits may be used to receive continuous waves if the retroactive coupling is increased sufficiently to cause self-oscillation.

It may be noted that when both grid and anode oscillatory

circuits are tuned by means of a variable condenser the mistuning required to produce a beat note may be accomplished by either condenser.

Tests for Self-Oscillation.—Before commencing to listen-in for a C.W. transmitter, it will frequently be helpful to know whether or not the vacuum tube of the receiver is actually oscillating or not. If it is not, it is no use trying to receive continuous waves. The following practical tests will show when the circuits are oscillating.

(1) On touching the aerial terminal a sharp click should be heard.
(2) If the aerial turning inductance is variable in studs, clicks should be heard when the switch is moved across the studs in use.
(3) If the variable condensers short when turned to 0° or 180°, clicks will be heard.
(4) A faint rustling sound will be heard in the 'phones
(5) All spark stations will appear to have a low hoarse note, whatever their original spark-frequency.
(6) A steady note will be heard in the 'phones of a suitably tuned C.W. wave-meter. This test will be explained later.
(7) If a delicate galvanometer reading up to about 0·5 milliamperes is included in the grid circuit of the valve a sharp deflection will be noticed the moment the valve oscillates of its own accord. This is due to the oscillations in the grid circuit being rectified to a certain extent. A Weston No. 375 galvanometer is very suitable for this purpose.

In the event of the above tests failing, the reason may be due to one of the following circumstances.

(1) The anode voltage may not be sufficiently high to produce self-oscillation.
(2) The filament current may be too small.
(3) The coupling between anode and grid oscillatory circuits is too loose.
(4) The coupling may be reversed. If a retroactor coil is used, then connections should be reversed or the coil itself reversed in order to see if the circuits will oscillate.
(5) The vacuum tube itself may not be suitable for use as a generator of oscillations.

(6) The representative point may not lie on a suitable portion of the grid-voltage—anode-current characteristic curve.

Practical Two-Valve C.W. Receivers.—Fig. 235 shows a

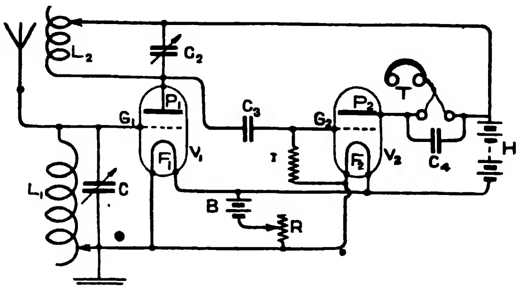


FIG. 235.—Practical two-valve C.W. receiver.

practical C.W. receiver using two vacuum tubes. The first acts as an amplifier and self-heterodyner. Beats take place in the circuit L_2C_2 and are rectified by the second valve which is arranged in the usual way. The first tube is not meant to act as a detector. The circuit has the disad-

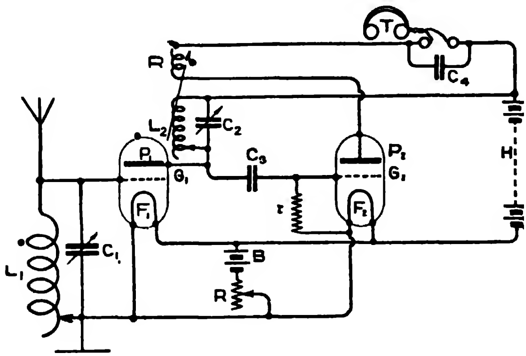


FIG. 236.—Two-valve C.W. receiver which does not radiate waves from the aerial.

vantage of emitting feeble continuous waves while receiving. The coil L_2 may be made aperiodic if desired.

Fig. 236 is another circuit which the reader may arrange. It is more efficient than the Fig. 235 circuit and does not radiate continuous waves. The incoming waves

are amplified in the anode oscillatory circuit L_2C_2 of the first vacuum tube. The second valve acts as a detector. In its anode circuit is an aperiodic retroactor coil R coupled to the coil L_2 sufficiently tightly to set up continuous oscillations. The frequency of these locally-generated oscillations may be altered by varying the condenser C_2 and the inductance L_2. These local oscillations interact with the magnified oscillations already taking place in L_2C_2 and produce beats which are then rectified by the second valve and give signals in the telephones T. The circuit L_2C_2 cannot, of course, be made aperiodic.

Fig. 237 shows a receiving circuit which is very selective on account of the loose coupling between the anode oscillatory circuit of the first vacuum tube and the grid oscillatory circuit of the second.

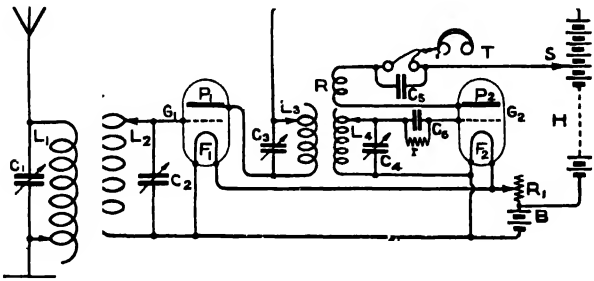


FIG. 237.—Selective two-valve C.W. receiver with tuned inter-valve oscillation transformer.

The retroactor coil is now coupled to the grid oscillatory circuit of the second valve. The coil L_3 may be made aperiodic if desired. The principle of this circuit may be applied to the various high-frequency detector-amplifiers previously described.

A Three-Valve C.W. Receiver.—Fig. 238 shows a circuit arranged by the author for a certain purpose. The incoming oscillations are amplified by the first vacuum tube and heterodyned by the second. They are then rectified by the third, which is adjusted to act as a detector. The first two tubes are not meant to rectify.

Combined Retroaction and Self-Heterodyning Circuit.—A more efficient method of using three valves to receive continuous waves is to employ retroactive amplification before the oscillations are heterodyned. Such a circuit has

been arranged by the author in Fig. 239. The circuit operates as follows: Incoming oscillations in L_1 are amplified in the anode oscillatory circuit R_1C_2 of the first vacuum tube. The inductance R_1 is coupled to L_1 in such a manner as to

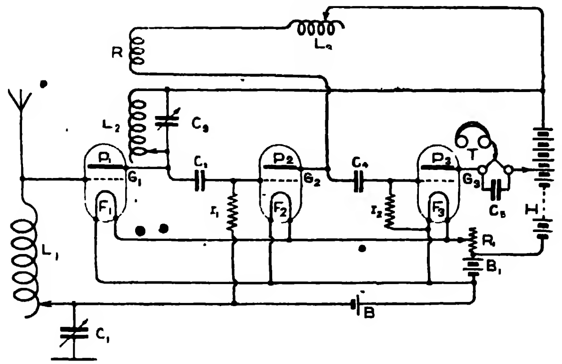


FIG. 238.—Three-valve C.W. receiver in which the second valve acts as heterodyner.

amplify further the incoming oscillations by retroaction. Self-oscillation should not be produced in the first tube. The magnified oscillations are once more magnified by the second vacuum tube and appear in the circuit containing C_3, where they are now heterodyned by the third valve, which is

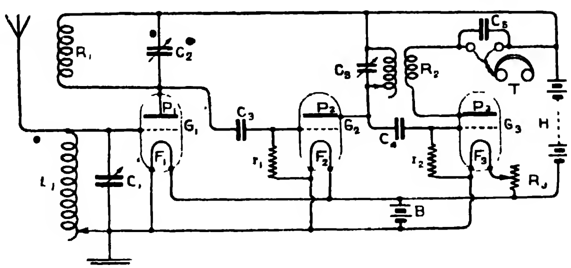


FIG. 239.—Three-valve C.W. receiver in which the last vacuum tube acts as detectordyner.

made to oscillate by coupling R_2, which may be aperiodic, sufficiently tightly to the inductance shunted by C_3. The third valve acts as the detector. When receiving long waves it may be advisable to connect a separate inductance in series with R_1.

Use of Detector-Amplifier.—If it is desired to use a detector-amplifier (a rectifying valve followed by others used as L.F. amplifiers) it is necessary to use an external heterodyner or to arrange a grid oscillatory circuit coupled to the anode oscillatory circuit of a separate vacuum tube. The latter arrangement is shown in Fig. 240. The separate vacuum tube is used simply as a high-frequency amplifier and self-heterodyner. The amplifier, which is of the Fig. 199 type (terminals X and Z) acts as the detecting device. The connections to the amplifier should be reversed to see which way gives the best results. This, incidentally, should be done on all amplifier circuits, since one arrangement generally gives rather better results than the other. The terminal connected to the grid should invariably be connected to the high-potential end of the coil to which the detector-amplifier is connected. It should not be connected to the end nearest the filament.

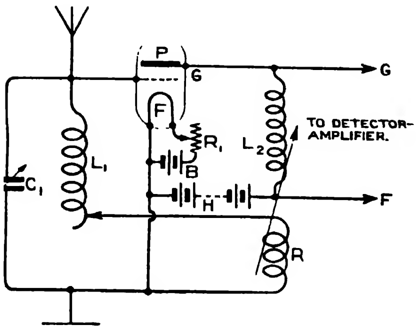


FIG. 240.—Circuit suitable for use with detector-amplifier for reception of C.W.

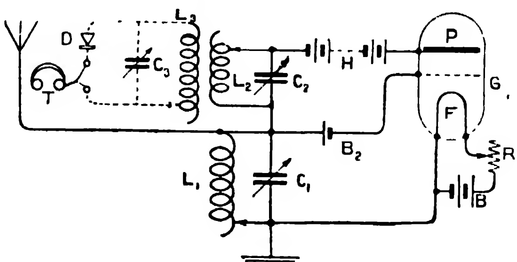


FIG. 241.—Highly selective C.W. receiver.

A Highly Selective C.W. Receiver.—Fig. 241 is a highly selective circuit which is of a type described by L. A. Hazeltine.* As will be seen the anode oscillatory circuit L_2C_2 is connected

* L. A. Hazeltine, *Proc. I.R.E.*, 6, 2, 91 (April, 1918).

across grid and anode of the vacuum tube and not across anode and filament as is more usual. This circuit will tend to absorb oscillations of frequencies to either side of the frequency desired and is therefore highly selective. Hazeltine does not recommend the use of the same valve as a detector but suggests using a separate detector circuit loosely coupled to L_2C_2. This detector circuit may consist, if desired, of a self-heterodyning vacuum tube, in which case the coupling between L_1 and L_2 is adjusted to give retroactive amplification. This class of circuit may be varied in many ways. The reader is referred to Figs. 149 and 150.

Phenomenon of Circuits Oscillating at Two Frequencies.—Circuits of the following types oscillate continuously at a *single* frequency when the coupling between grid and anode oscillatory circuits is sufficient to produce self-oscillation.

(1) Circuits in which the grid circuit is tuned and the anode circuit aperiodic (*e.g.* Fig. 232, oscillator of Fig. 223).

(2) Circuits in which the anode circuit is tuned and the grid circuit is aperiodic (*e.g.* oscillator of Fig. 222).

(3) Circuits in which the grid and anode oscillatory circuits are part of one circuit, the tuning being accomplished by a single condenser as in the case of the oscillator of Fig. 228.

(4) Circuits like that of Fig. 148 (*j*), in which the secondary inductance is directly in the aerial circuit and not as shown; or the circuit as it stands without the aerial circuit coupled to it.

The frequency of the oscillations set up will depend in cases (1) and (2) on the wave-length to which the tuned circuit is adjusted. In the case of (3) the frequency will depend on the product of the capacity and the sum of the two inductances, to which latter has been added the mutual inductance between the coils (if any). In case (4) the frequency will depend on the product of the inductance and the combined capacities of the condensers.

When we come to use circuits in which both grid and anode circuits are tuned (*e.g.* Fig. 148 (*d*)) and circuits using aperiodic retroactors but loosely coupled to an aerial circuit (*e.g.* Fig. 148 (*a*)), we find that the local oscillations are liable to take place at two different frequencies. Sometimes the circuits will oscillate at one frequency and sometimes at the other.

Sometimes they take place at the same time. The whole theory of oscillating circuits and their frequencies is given in Hazeltine's Paper * before the Institute of Radio Engineers and reference should be made to it for full information.

The phenomenon of the production of two frequencies in a receiving circuit is sometimes of great use. We have seen that the self-heterodyne circuit has the disadvantage of being slightly out of tune with the incoming waves and therefore offers some reactance. If, however, we arrange for the vacuum tube to be ready to oscillate at two frequencies, we can make one frequency coincide with the incoming frequency (in which case there will be no reactance) and make the other frequency slightly different in order to obtain beats.

The effect is frequently obtained when the aerial and closed receiving circuits are closely coupled. Considerably louder signals are the result of the phenomenon. L. W. Austin has used what he has termed a "sensitizing circuit" which appears to act in the above manner under certain conditions. It enables the coupling between the aerial and closed receiving circuits to be loose. His arrangement consists in coupling an inductance shunted by a variable condenser to an inductance coil connected in the grid oscillatory circuit.

Use of Resistance Amplifiers as C.W. Receivers.—The resistance detector-amplifiers described in Chapter VI. and Chapter VIII. may be used to receive C.W. signals provided an external heterodyner is used or if the retroaction is sufficiently increased to produce self-oscillation.

Fig. 211 may be used as a C.W. receiver provided R is coupled sufficiently tightly to L_1. The amplifier will then oscillate of its own accord at a variable frequency. Similarly the circuits of Fig. 213 type may be used to receive continuous waves if the degree of retroaction obtained by means of the resistance or capacitative coupling is sufficiently increased.

* *Proc. I.R.E.*, April, 1918.

CHAPTER XI.

Transmission of Continuous Waves with Vacuum Tubes.*

Just as there are an almost infinite number of circuits which may be used for retroactive amplification and for the reception of continuous waves, so are there many methods whereby continuous oscillations may be generated by means of vacuum tubes. Since almost every C.W. receiver employs an oscillating vacuum tube to generate local oscillations, we can see that if we increase the output of these oscillators we will obtain a useful transmitter of continuous waves. There seems a little doubt as to the efficiency of high-power vacuum tube transmitters at the present time. Much energy is wasted in heating the filaments of the transmitting tubes and it appears that high-frequency alternators have a higher efficiency. As a generator of small and medium power the vacuum tube is ideal and its efficiency considerable.

Advantages of Continuous-Wave Communication.—Before passing on to technical considerations, it will be interesting to notice the advantages gained by the use of continuous waves. They may be enumerated as below:

(1) They are usually capable of travelling further distances and are not liable to be absorbed to the same extent as damped waves.

(2) They are capable of being received by the heterodyne principle. The results of using heterodyne reception are well known.

(3) The use of heterodyne reception renders C.W. working very selective on wave-lengths lower than about 3,000 metres. A very large number of stations are able to work in a limited area without causing interference.

(4) On account of the absence of damping, tuning is more selective.

* See, also, J. Scott-Taggart, "Practical Notes on Small-power C.W. Sets," *Wireless World*, April, May, June, 1919.

(5) By using the principle of beat reception, C.W. signals may be given any desired pitch. They may consequently be easily read through atmospherics or strays.

(6) On account of the persistency of continuous waves, the receiving circuits may be very loosely coupled, thus minimising interference and the effects of strays.

(7) High-speed of transmission is possible. In the case of "spark" wireless transmitters, only one or two sparks would take place during a "dash" if the sending were too rapid and no musical note would be heard at the receiving station.

(8) In the case of vacuum tube transmitters there is no loss of energy due to the resistance of a spark gap.

(9) C. W. transmitters may be converted into wireless telephone transmitters.

The Oscillating Vacuum Tube.—There is much controversy at present as to the first investigation to discover the oscillating properties of the three-electrode tube. L. De Forest, E. H. Armstrong, J. L. Hogan, I. Langmuir, and A. Meissner all claim the distinction. There seems a good deal of evidence to show that de Forest in his experiments discovered this useful property of the audion, although its great usefulness was not fully appreciated till later. It is certain that his audion circuits were capable of generating oscillations, and he certainly understood the retroactive effect between grid and plate. Long before this the "buzzing telephone" was known. This device is simply a microphone and telephone in a common circuit and placed together. The resultant low-frequency self-oscillation is purely a form of retroaction in which the output of the amplifier (the microphone) is coupled to the input side. In the same way, if new types of high-frequency amplifier are produced we will be able to use them as oscillators. Langmuir's British Patent claiming a method of making a valve oscillate is 144647 (Oct. 29/13).

Telefunken Oscillating Circuits.—Fig. 242 shows an arrangement described by A. Meissner,* of the Telefunken Company. This type of circuit is described in German Patent 291604 (April 10/13). By coupling a coil L_2 to a grid

* See *Electrician*, July 31/14, and L. de Forest's comments, *Electrician*, Aug. 28/14.

coil L_3 and the anode oscillatory circuit L_4 to the coil L_1, Meissner obtained continuous oscillations. The action of this circuit is very similar to the various oscillatory circuits we have previously discussed. If a momentary oscillation is set up in the circuit L_1L_2C it is passed on to the grid oscillatory circuit L_3. It is now amplified by the vacuum tube and reappears in L_4. The coupling between L_4 and the circuit L_1L_2C acts in a retroactive manner and strengthens the original oscillation. The strengthened oscillation is further amplified and the process is repeated until the whole circuit oscillates of its own accord.

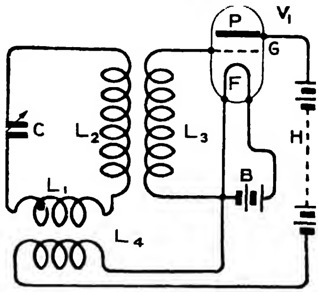


FIG. 242.—Meissner's oscillating circuit

In British Patent 252/14 (Jan. 5/14), G. von Arco and A. Meissner describe how they employ the phenomenon of retroaction to produce continuous waves for wireless transmission. The circuit suggested is shown in Fig. 243. This is also the circuit described in the German patent of earlier date. A grid coil L_1 is provided and also an anode oscillatory circuit L_2C_1 coupled to it. An aerial and earth are connected to the circuit L_2C_1 in order that the continuous oscillations set up may be used to radiate continuous waves into space. A source of potential H, which may be an anode battery or dynamo, is included in the anode circuit PL_2HB. A tapping key is used for signalling and is arranged to make and break the anode circuit. If the key be closed a sudden flow of anode current will pass through the anode circuit and charge the condenser C_1, which will discharge through L_2 and thus set up a few oscillations in the circuit L_2C_1. Since the inductance L_1 is coupled to the coil L_2, the oscillations in L_2C_1 will induce into the grid coil L_1;

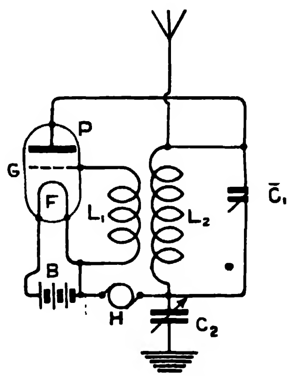


FIG. 243.—Arco and Meissner continuous-wave transmitter.

they will be amplified by the vacuum tube and passing round the anode circuit L_2C_1 will strengthen the original oscillations in L_2C_1, which would normally die out rapidly. The strengthened original oscillations induce into L_1,* are amplified once more, and the process is repeated until the circuits oscillate of their own accord and a state of equilibrium is reached. The building up of the continuous oscillations takes a negligible time and will only take place when the coupling between L_1 and L_2 is sufficiently tight. The energy from the anode battery converted into oscillations in this manner can be taken from the circuit L_2C_1 and led to an antenna connected directly to it as shown.

The wave-length emitted will depend on the value of the condenser C_1. The energy generated will depend to a certain extent on the coupling between L_1 and L_2. If this coupling is loose, the representative point on the anode current curve will only travel up and down the anode curve a short distance. The maximum power is generated when the representative point moves along the whole length of the straight portion of the curve. The power generated by such a system depends on the length of the straight portion of the curve; in other words, on the strength of the current flowing from the cathode (the filament) to the anode (or plate). To obtain suitably high potentials on the anode Arco and Meissner suggest the use of low-frequency alternating current. In this case the voltage is easily stepped-up by a transformer, but oscillations will only take place when the positive half-cycle applies its E.M.F. to the anode. These questions are discussed at length later.

Armstrong's Circuits.—E. H. Armstrong has evolved a large number of oscillating circuits which are capable of being used as transmitters. An example is given in British Patent 24231/14 (Dec. 18/13), which has been previously mentioned In Armstrong's patent, the arrangement could be used as a transmitter by coupling the aerial circuit to the inductance and placing a key in the anode circuit. Stronger oscillations take place in the anode circuit, and on that account the aerial circuit is connected or coupled to it.

Marconi Vacuum Tube Transmitters.—In British Patent 13247/14 (May 29/14), H. J. Round and Marconi's Wireless Telegraph Co. show a valve transmitter in which the grid of the tube takes the form of an external metal coating.

* The "maintaining potentials" may be amplified first before communicating them to the grid. See J. Scott-Taggart, *Electrical Review*, Jan. 7, 1921.

In British Patent 13248/14 (May 29/14), the Marconi Company and H. J. Round describe several circuits for the production of continuous waves. They involve the use of a battery and resistance across the grid condenser. This arrangement was found useful when the soft valves then used were employed.

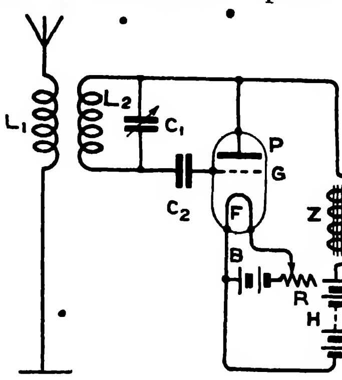


FIG. 244.—A Lee de Forest C.W. circuit.

Lee de Forest's Circuits.—Lee de Forest describes in British Patent 6486/15 (April 30/15) an arrangement for the transmission of continuous waves generated by his audion. Connection is, as is usually found in de Forest's circuits, taken from L_2C (Fig. 244) to the grid and plate of the audion. In the plate circuit is connected a plate battery H and an iron core impedance Z. The action of the circuit is a little obscure, but continuous oscillations are set up in L_2C_1 and are transferred to the aerial circuit. The audion used with this circuit contained residual gas. The condenser C_2 in this class of circuit serves to insulate the grid from the steady voltage of H. In British Patent 1014/15 (Sept. 4/15), de Forest describes a circuit which he uses for telephonic transmission. A resistance and microphone is connected across G and F of an "oscillion" (the trade name of a hard "audion").

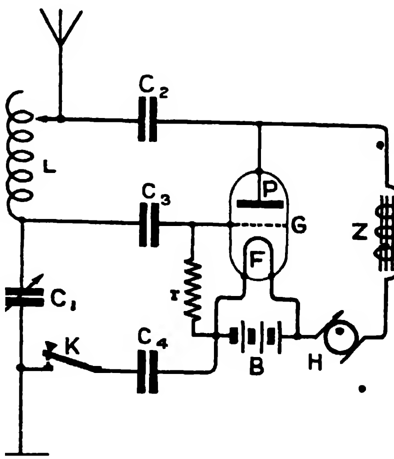


FIG. 245.—Another de Forest C.W. transmitter.

Fig. 245 is another circuit designed by Lee de Forest and C. V. Logwood and described in British Patent 107001 (May

23/16). A resistance r is connected directly across grid and filament and acts as a leak to prevent the grid becoming too negative. A key K is used for signalling. The usual iron-core impedance coil Z is included in the plate circuit. This arrangement resolves itself into a simple oscillatory circuit if we rearrange the circuit, omitting C_2, C_3, and C_4.

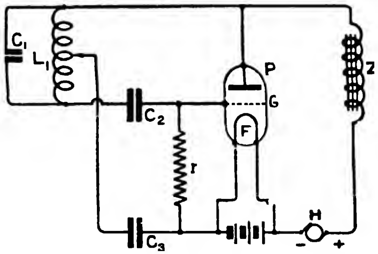


FIG. 246.—A form of C.W. transmitter patented by de Forest.

Fig. 246 shows another de Forest circuit described in the same patent.* The condenser C_1 represents the antenna-earth capacity. A connection is taken from a point on the inductance L_1 to the filament. The stopping condenser C_3 avoids short-circuiting the source H of the E.M.F. on the plate P. Two more suggested circuits are given in the specification ; one is shown in Fig. 296.

Practical Continuous-Wave Transmitter.—We may use almost any kind of retroactive circuit to produce continuous waves. Probably the most useful type of circuit is that shown in Fig. 247, in which retroaction is obtained by coupling magnetically the anode and grid oscillatory circuits of a hard vacuum tube. The following points should be noted about this circuit.

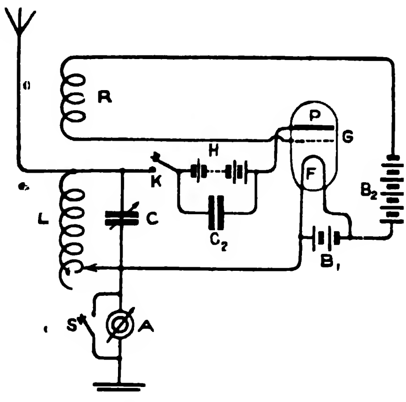


FIG. 247.—A practical small-power C.W. transmitter.

(1) The aerial circuit is *directly coupled* to the anode oscillatory circuit. It is unnecessary to have a separate aerial circuit loosely coupled to the anode oscillatory circuit. The reasons which necessitate

* See also British Patent 141046 (June 1/15) of R. V. L. Hartley.

this latter arrangement in an ordinary spark set do not apply.*

(2) The anode oscillatory circuit is tuned by means of the condenser C_1, which varies the length of the waves emitted. The value of C_1 should be as small as possible.

(3) The grid coil R is aperiodic. The coupling between R and L is variable. The coil R may be wound of resistance wire or may be shunted by a resistance to make it aperiodic. This increases the range of wave-lengths over which the vacuum tube will oscillate. The coil R is now not strictly an oscillatory circuit, but is used for communicating high-frequency *potentials* to the grid G.

(4) The anode battery H, which may have a value of 200 to 800 volts for small sets working up to about 50 miles, is shunted by a condenser C_2 to allow the passage of H.F. oscillations. Instead of a battery a direct current dynamo might be used. It is usually preferable to place H on the filament side of L.

(5) A grid battery B_2 may be provided to assist in the prevention of a grid current. To obtain the full power from the set, the operating point should be half-way along the steep straight portion of the anode current curve. A leaky grid condenser is usually used instead of B_2.

(6) An ammeter A of the hot-wire type is included in the earth lead to measure the current in the aerial. In the case of a small-power set this current will be anything up to 1 ampere. An ordinary flash lamp bulb may be used in place of A. It will light up on pressing the key K and will give a very good indication of the relative strength of the aerial current. The switch S shorts A when desired.

(7) The method of signalling is to make and break the anode circuit by means of the key K. The moment K is closed the circuit oscillates of its own accord if the coupling between R and L has been suitably adjusted. If the connections to R have been wrongly made the circuit will not oscillate.

Modifications of Previous Circuit.—Fig. 248 shows another practical circuit for low-power transmission. Various features

* This feature has been described by M. Latour in British Patent 147462 (Nov. 11/15).

have been shown on it in order to illustrate one or two variations or refinements. Interesting features to be noted are:

(1) The inductance L_1 has two sets of variable tappings taking from it. T_1 goes to the aerial and T_2 to the anode. Sliding contacts may be used but radial switches and tappings are to be preferred. The tapping T_2 is sometimes termed the *anode tap.* The arrangement is simply the ordinary auto-transformer coupling sometimes used in spark transmitting and receiving circuits. It results in more efficient transmission.

(2) The grid oscillating circuit is now made tuned by the addition of the condenser C_2. This complicates

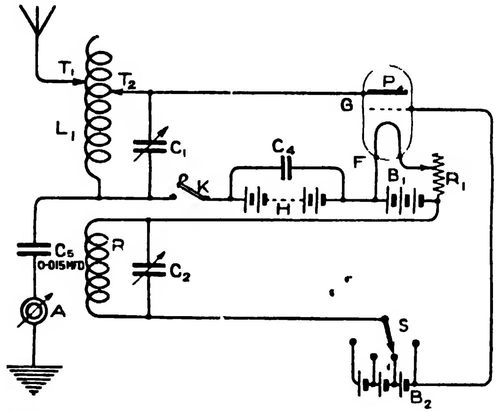


FIG. 248.—A C.W. transmitter provided with an anode tap.

the tuning of the circuit and is best omitted. The condenser C_2 may be calibrated in wave-lengths.

(3) The switch S and the battery B_2 provide a means of adjusting the grid potential to the value which gives the maximum aerial current in A.

(4) A resistance of about 8,000 ohms is usually beneficial if connected in the grid circuit in place of the arrangement SB_2. It may be non-inductive or simply a bobbin of fine insulated copper wire without an iron core. It is shunted by the condenser of about 0·001 to 0·002 mfd. to allow the passage of H.F. currents. The use of this arrangement lessens the current running in the grid circuit; it prolongs

the life of the valves and lessens the chance of the "blue glow" phenomenon produced when a hard valve becomes soft. It also tends to keep the grid at a suitable negative potential.

(5) A fixed condenser C_5 of about 0·015 mfd. is connected in the earth lead. Its function is to prevent the positive side of H being connected to earth. This difficulty can be obviated by connecting the anode battery in the position shown in Fig. 282. In certain cases it is of advantage to have C_5 variable in steps.

(6) The negative side of the anode battery is connected to the positive side of the filament heating accumulator. This adds the voltage across B_1 to that of H.

Single-Coil C.W. Transmitters.—Instead of using two separate coils coupled to each other, it is possible to use only one coil which has a variable tapping. Fig. 249 shows an exceedingly simple vacuum tube transmitter. A tapping T slides along the inductance L and is connected to the filament of the vacuum tube and also to earth. The anode oscillatory circuit consists of the top portion of the coil L above T. The grid oscillatory circuit consists of the lower portion below T and is aperiodic. The circuit has a condenser C across the anode oscillatory circuit. The tapping T need not be a sliding contact. A radial switch may be provided with several studs connected to different points of L.

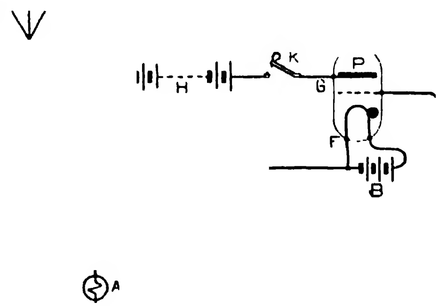


FIG. 249.—Simple single-coil C.W. transmitter.

Another single coil C.W. transmitter is shown in Fig. 250.* The condenser C is now connected across the whole of L. The earth connection is taken to the point B. The variable condenser C assists in the tuning of the set to a given wave-length.

* See British Patent 141046 (June 1/15), by R. V. L. Hartley (Western Electric Co.), also 107001 (May 23/16) of L de Forest and C. V. Logwood, and also 149145 (July 16/17) of Huth Ges.

This class of circuit, claimed by R. V. L. Hartley, is very useful since it does not employ a retroactor coil. Broadly, it is a single circuit across grid and anode, a connection to the filament being taken from a point on the inductance. The two portions of the inductance need not be magnetically coupled. By this arrangement the potentials communicated to the grid are such as to maintain oscillations in the single circuit.

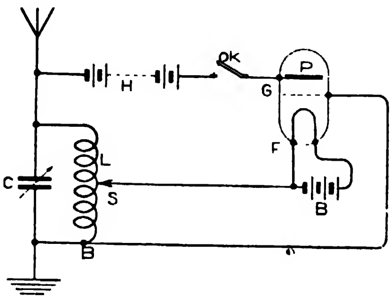


FIG. 250.—Another simple C.W. transmitting circuit.

A rather analogous circuit is claimed by E. H. Colpitts in British Patent 141060 (Feb. 1 18). The filament is now connected not to a point on the inductance but between two condensers in series, which shunt the single inductance used. A suitable path for the direct anode current is provided.

Capacitative Coupling in C.W. Transmitters.— We saw in Fig. 135 how electrostatic or capacitative retroaction could be obtained by connecting a small condenser across the grid and anode of a vacuum tube.* We also saw that under certain conditions the valve could be made to oscillate of its own accord. In actual practice the use of capacitative retroaction provides us with an efficient and variable method of coupling anode and grid oscillatory circuits of a C.W. transmitter.

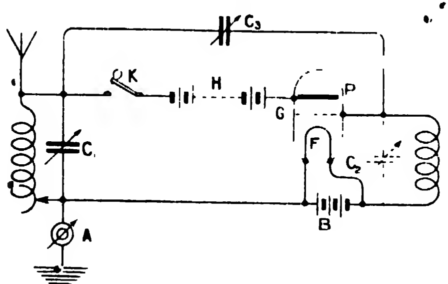


FIG. 251.—C.W. transmitting circuit employin capacitative coupling.

Fig. 251 shows a theoretical circuit in which a coupling condenser C_3 is used. The grid coil L_2 may be aperiodic or may be tuned by the addition of C_2 as shown by the

* See also L. de Forest's Patent 107001 (May 23/16).

dotted lines. The condenser C_3 is adjusted until the circuits oscillate of their own accord and the maximum aerial current is obtained. The wave-length emitted may be varied by adjusting the inductances and condensers. The combination which gives the maximum current in the aerial should be used, although other combinations giving the same wave-length will frequently be obtained. Variation of C_3 will not only alter the coupling, but also the frequency of the local oscillations. The action of this class of circuit is not very regular unless the coils L_1 and L_2 are slightly coupled to each other in the ordinary way. The coupling need not be variable.

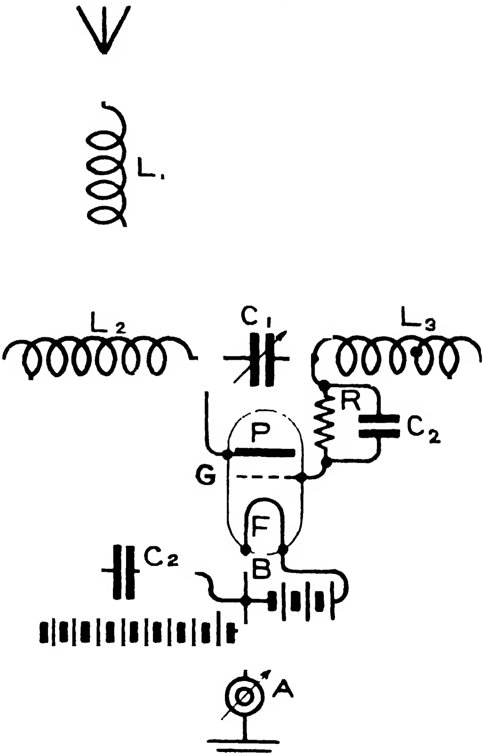


FIG 252.—Practical C.W. transmitter using magnetic and capacitative coupling.

Fig. 252 is a circuit similar to a type used by the French Government There is no particular novelty about it, but it is a simple and efficient circuit. The vacuum tube is made to oscillate by means of the capacitative coupling C_1 and also by slightly coupling the coils L_2 and L_3. The coils L_2 and L_3 may be fixed or variable in one or two steps as shown. The length of the waves emitted may be varied by tuning on the inductance L_1. It may consist of a variometer, a coil with a sliding contact or an inductance provided with a 10-turn switch and a 1-turn switch. The condenser C_1 is adjusted to give the maximum current in the

aerial. The longer the waves emitted the greater will have to be the capacity of C_1. A grid resistance R shunted by C_2 is shown, but it is a refinement and not essential with some types of valve. A grid potentiometer arrangement could be substituted if desired. Having shown what variations are possible, it is hoped that the student readers themselves will be in a position to modify circuits as they desire.

Separation of H.F. and Direct Current in C.W. Transmitters.—At the end of Chapter VI. we saw various methods of separating the high-frequency oscillatory current in an anode circuit from the normal steady anode current. The devices shown in Fig. 183 are all very useful when used in C.W. transmitting circuits.

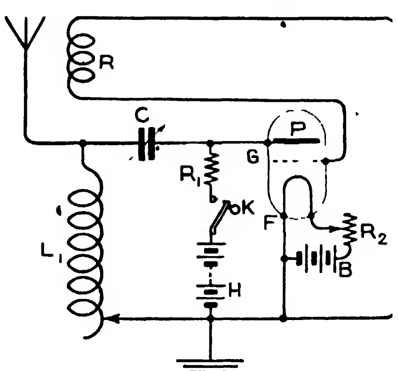


FIG. 253.—C.W. transmitter in which the anode oscillatory circuit is shunted across the D.C. anode circuit which contains a high resistance.

Fig. 253 shows a practical example of a high-frequency circuit separated from and coupled to the anode circuit PR_1KHF by the condenser C. The condenser C allows the passage of high-frequency oscillations but acts as an insulator towards the direct anode current. If the aerial is touched when the key K is depressed, only the high-frequency current will be felt and not the actual voltage of H, as would be the case if the Fig. 253 circuit were used. Moreover, there will be no leakage of direct current from the aerial if the insulation of the latter is faulty. The essential feature of this circuit is the use of a resistance R_1 which has a value of about 50,000 ohms, or more if the internal resistance of the vacuum tube between filament and anode is high. This resistance allows the passage of direct current but tends to oppose high-frequency oscillations. The high-frequency E.M.F.'s across the resistance R_1 energise the aerial oscillatory circuit. The greater the resistance of R_1 the greater will be the E.M.F.'s across it, but, as we saw in the case of resistance amplifiers, the introduction of a high resistance in the anode circuit

cuts down the anode current by perhaps as much as half and necessitates the use of higher anode voltages. The battery H, or whatever source of E.M.F. is employed, is also included in the anode circuit shunted by the oscillatory circuit. This arrangement saves the use of a separate by-path condenser across H, which would be necessary if the oscillatory circuit were simply connected across R_1.

The disadvantage of this class of circuit is the high E.M.F. required to operate it, and the loss of power in the resistance. The drop in potential across R_1 is very considerable and consequently the circuit is not suitable for use when the source H of E.M.F. consists of a battery of accumulators or dry cells. We can, however, use a different arrangement by substituting an iron-core impedance or air-core choke-coil in place of the resistance R_1. The impedance offered to high-frequency currents by this coil would cause the radio-frequency E.M.F.'s across it to energise the oscillatory circuit. Since the resistance of this choke-coil to the direct anode current is small compared to the internal resistance of the filament-anode path inside the vacuum tube, the usual anode voltage only is necessary.

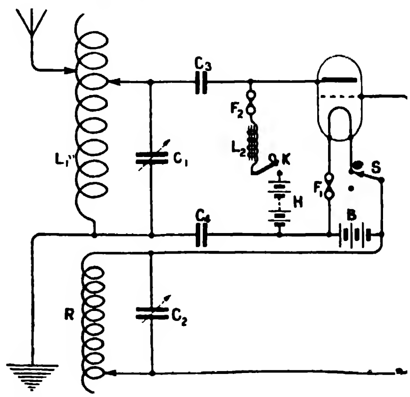


FIG. 254.—C.W. transmitter in which the anode oscillatory circuit is shunted across the D.C. anode circuit, which contains an iron-core choke-coil.

The principle of the resistance circuit of Fig. 253 is used by the Western Electric Company in some of their receivers (see British Patent 102500, Fig. 4). If an impedance coil is used we have a circuit similar to that employed by Roy A. Weagant and also by A. Meissner. In the circuit shown, a variable condenser might be connected across L_1. A filament rheostat R_2 may be used to regulate the power. The retroactor R is shown aperiodic but might be tuned. Care should be taken not to let the condenser C short-circuit, otherwise the battery H will be shorted through L_1.

Fig. 254 shows the circuit of Fig. 253 modified. This time the oscillator circuit L_1C_1 is connected to the anode circuit by means of *two* stopping condensers C_3 and C_4, which may conveniently be of fixed capacity. The impedance coil L_2 might of course be replaced by a resistance. A switch S

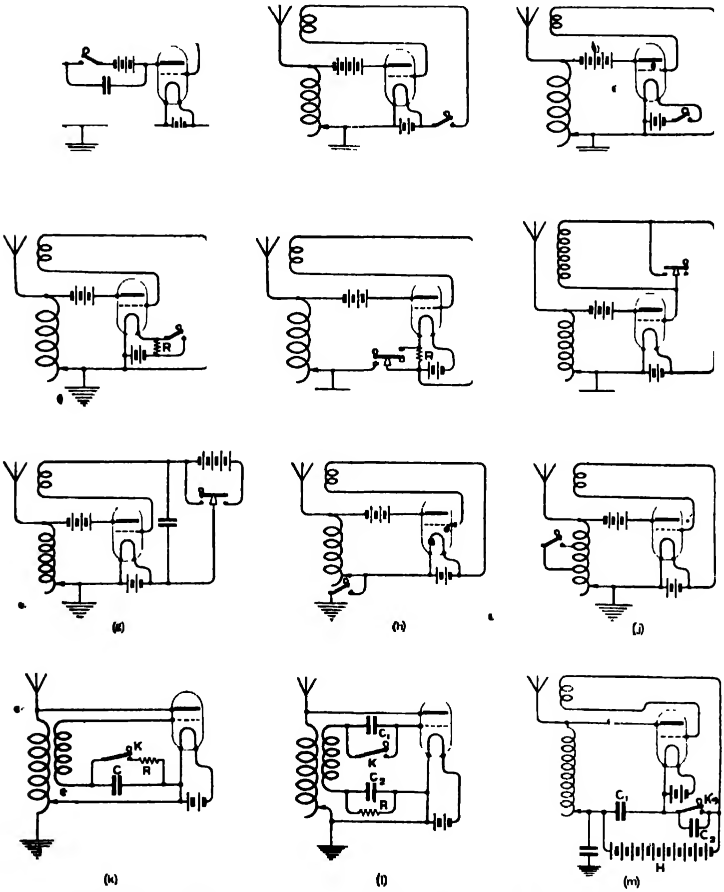


FIG. 255.—Various methods of signalling with a tapping key.

is used to switch the filament current on or off. A fuse wire F_1 is connected in the filament circuit and blows if the filament current is made too great. The filament of the vacuum tube is thus protected. Another fuse wire F_2 is shown in the anode circuit and blows if the anode current

increases above a certain limit. The battery H is thus protected. In Fig. 254 the grid oscillatory circuit is shown tuned.

This general class of circuit has been used by the Telefunken Company and also in circuits developed by E. H. Colpitts for the Western Electric Company (see Fig. 294).

Methods of Keying.—Various methods of sending out dots and dashes from a C.W. transmitting station have been suggested. Some of them are given below. They are illustrated by Fig. 255.

(*a*) A key is inserted in the anode circuit of the vacuum tube. On depressing the key, the anode current begins to flow and the system oscillates. On raising the key, the anode current stops flowing and the self-oscillation ceases. This method is very convenient for small powers. Current is only taken from the anode battery when sending. Sparking at the key contacts (which may be lessened by connecting a condenser across them), occurs when heavy anode currents are used.

(*b*) A key may be included in the grid circuit. The system will only oscillate when the key is depressed. The key does not now interrupt heavy currents and no sparking occurs. The anode current, however, will be flowing all the time to a certain extent.* This causes the plate battery to "run down" rapidly. Also, the steady plate current will rapidly heat up the anode by electron bombardment; the anode may become white hot; this results sometimes in the liberation of occluded gas, which renders the vacuum tube useless for transmission. When method (*a*) is used the anode has time to cool between the dots and dashes during transmission.

(*c*) A key may be included in the filament circuit. This arrangement is very economical since neither anode nor filament current is being wasted in between the dots and dashes. Slow sending only is possible since it takes an appreciable time for the filament to heat up and cool down. It involves a great strain on the filament which rapidly burns out. This method is consequently not used in practice.

* Sometimes the grid accumulates a sufficiently negative potential to cut down the anode current.

(*d*) An improved modification is to keep a steady current flowing through the filament which, however, is made insufficient to set up self-oscillation. The key circuit is so arranged that on pressing the key the full filament current is switched on. A suitable arrangement is to have a resistance in series with the filament battery; on pressing the key this resistance is shorted.

(*e*) Combinations of (*a*) and (*b*) may be used, though no benefit is gained. A combination of (*a*) and the improved modification described in (*d*) is useful since it economises filament current. The filament resistance should be shorted just before the anode circuit is closed (see (*d*)).

(*f*) The grid or anode oscillatory circuit may be normally shorted. On pressing the key the system is free to oscillate. The disadvantage described in (*b*) is present.

(*g*) The key may be connected in the grid circuit in such a way that a battery is brought into the circuit and gives the grid a strong negative potential which prevents the circuits oscillating. On depressing the key the battery is taken out of circuit and the system is free to oscillate.

(*h*) A key might be connected in the aerial circuit in the case of low powers.

(*j*) Any of the circuits may be normally detuned. On pressing the key the correct wave-length is emitted. This system is employed on arc transmitters and is most undesirable since two wave-lengths are being used and cause considerable interference with other stations. One or two turns of the aerial tuning inductance are usually shorted by depressing the key. In this way a wave-length is emitted different to that radiated between the dots and dashes. The receiving station tunes his set to the shorter wave-length, and does not hear the spaces unless he specially tunes his set to them. The difference between the two wave-lengths is usually about 100 metres, but frequently it is more.

(*k*) A key may be inserted in series with the resistance of the grid leak, both leak and key are shunted by the

grid condenser. On raising the key the oscillating potentials on the grid will, by making the grid positive half the time, cause a large accumulation of electrons on the grid, which will become so negative that the anode current will be cut off and the system will stop oscillating. This happens almost instantaneously, and the arrangement has been very widely used.

(*l*) A modification consists in connecting a second condenser in the grid circuit. When signalling this is shorted by the key. The arrangement works on the same principle as the one above.

(*m*) An ingenious keying system has been described by N. Lea and J. Ree (of the Radio Communication Co., Ltd., London). The key is so arranged that any arc which forms across the key contacts on raising the key communicates a high negative potential to the grid. The arrangement is very effective in practice, and is suitable for high powers.

The Production of High Voltages. — The production of high voltages for C.W. transmission is a problem of great importance. The following methods of obtaining high voltages are in use at present:

(1) A battery of dry cells or accumulators.
(2) A direct current dynamo of high voltage and small output.
(3) Step-up transformers in the primary of which an intermittent current flows; an ordinary spark coil is an example.
(4) The use of alternating current the voltage of which can easily be stepped-up by the use of transformers and then rectified.
(5) The use of the positive half-cycles of alternating current.
(6) The use of high-voltage alternating current without rectification.

We will now consider individually the various methods which may be employed, and their relative merits.

High-tension Batteries.—For voltages up to about 400, the most suitable source of E.M.F. is a battery of cells or accumulators. A number of flashlamp batteries may be connected in series, carefully insulated. This arrangement,

however, will very soon "discharge" in use. For experimental work large dry cells of the best make should be used. The volume of each cell should not be less than 12 cubic inches. Owing to the deterioration of cells, it is preferable to use the type which requires to be filled with water before use. The greatest care should be taken to insulate each cell. The cells may be conveniently mounted in boxes of 70, giving about 100 volts per box. The necessary voltage is obtained by connecting several of these 100-volt batteries in series.

If the anode batteries are in constant use it is preferable to use accumulators, although they are cumbersome and require recharging. In spite of the fact that their initial cost is high, they are more economical in the end. Probably the most suitable kind of cell is the 3-ampere-hour size. They may be arranged in boxes of 50, all in series.

Dynamos.—Dynamos are frequently used to obtain the voltages required for C.W. transmission. They may be divided into three classes :

(1) Hand generators.

(2) Propeller-driven generators.

(3) Motor generators worked from an accumulator.

The first type provides high-voltage direct current by the turning of a handle.

The second class is used on aeroplanes, where weight is a consideration and where power is obtained by the use of a small propeller which rotates as the aeroplane passes though the air. Some extremely light and efficient dynamos for this purpose have been evolved. A difficulty with these sets is to obtain a uniform E.M.F., as the speed of revolution of the propeller is liable to vary.

The third class is the most common and is sometimes used on aeroplanes as well as land stations.

Use of Induction Coils to Obtain High Voltages.—A very useful method of obtaining the high voltages necessary for C.W. transmission is to employ an ordinary small induction coil the secondary terminals of which are connected in the anode circuit of the transmitting tube.

Fig. 256 shows the induction coil in use. An accumulator B_2 of about 10 volts works the induction coil T_1T_2, which is of the usual type, the step-up ratio, however, being only 1 to 100. The make-and-break is of the usual type and is shunted by a condenser C_3 of about 1 mfd. capacity. The

primary winding T_1 takes a current of two to three amperes. The secondary winding gives a voltage of about 1,000 and a current of about 20 milliamperes. It is shunted by a condenser C_2 of about 0·02 mfd., which serves the double purpose of allowing the H.F. oscillations in the anode circuit to pass and also of resonating the transformer T_1T_2 to the frequency of the make-and-break.

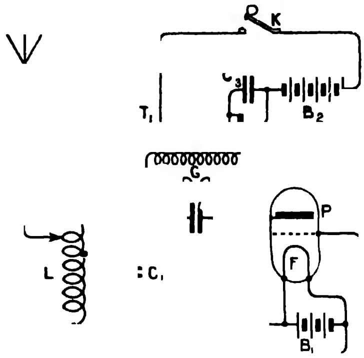


FIG. 256.—Use of an ordinary induction coil to supply the anode with high E.M.F.'s.

Now the current from the secondary of such a coil is not a sinusoidal alternating one. The current induced in the secondary coil is very much stronger at the "break" than at the "make." Consequently we connect the secondary T_2 in the anode circuit in such a way that the impulse at the break makes the anode positive. While the anode is positive an anode current is set up and the circuit commences to oscillate and radiate continuous waves. On the "make" a weaker negative pulse affects the anode, but as no anode current is established no oscillations are set up until the next positive pulse comes along. The result is that continuous waves are sent out in groups at the frequency of the "breaks" in the primary current. Fig. 257 shows the kind of waves emitted. The top line shows the variation of anode voltage. The negative voltage at the make is shown below the line. The second line shows the anode current, which only flows when the anode is positive. The third line shows the continuous waves emitted during the time that anode current is flowing. The waves very much resemble ordinary damped waves, except in that each group contains more waves than would be the case with damped wave-trains. It is to be expected that the oscillations would continue for a short time after the actual anode current has stopped. In Fig. 256 a safety spark gap G is provided. The gap is normally too wide for a spark to pass.

The aerial current obtained from the circuit of Fig. 256, using 6 volts across the filament and 1,000 volts on the anode, is about 0·7 ampere and will signal a range of about 20 miles. The aerial current is about the same as that obtained if an anode battery of 600 volts were used. The waves, being divided up into groups during transmission, may be received on an ordinary damped-wave receiver, such as a crystal detector circuit or non-oscillating valve. Best results, however, are obtained when heterodyne reception is employed. The signals heard then bear a resemblance both to spark signals and the usual note heard when receiving C.W. The note obtained with an ordinary vibrator is low and the signals are liable to be jammed by spark stations; the use of this class

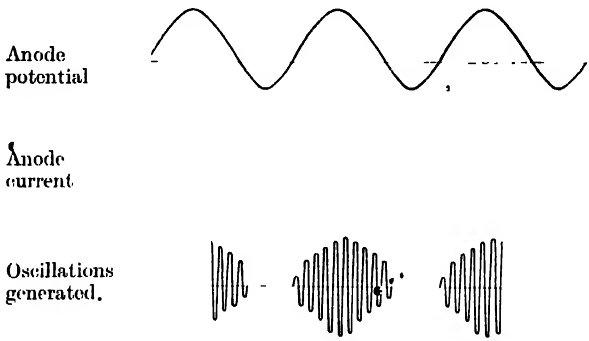


FIG. 257.—Type of oscillations generated by Fig. 271 circuit.

of transmitter causes serious interference with neighbouring stations and is therefore not to be altogether recommended for most purposes. Where lightness of equipment is essential the arrangement is excellent. It is, of course, very much cheaper to maintain than anode batteries.

An improved form of the Fig. 256 circuit is shown in Fig. 258. We are now using a better form of induction coil, the make-and-break of which consists of a rotating armature A (at the extreme right of the figure) driven by a small motor or water turbine. On pressing the key K a current passes through T_1 which may be interrupted at the rate of 1,000 times per second. The voltage of B_1 is stepped-up by the induction coil T_1T_2 and applied to the anode of the vacuum tube. The groups of waves radiated have now a frequency of 1,000 and will produce a clear, high note at the receiving station

even if heterodyne reception is not employed. With beat reception the signals are excellent and not very much different from those received from stations sending out pure continuous waves.

This system is sometimes known as the *tonic train* interrupted C.W. method of transmission. One of its features is that stations may be given characteristic notes by varying the speed of the make-and-break. When *pure* continuous waves are emitted, all stations sound alike, and one station

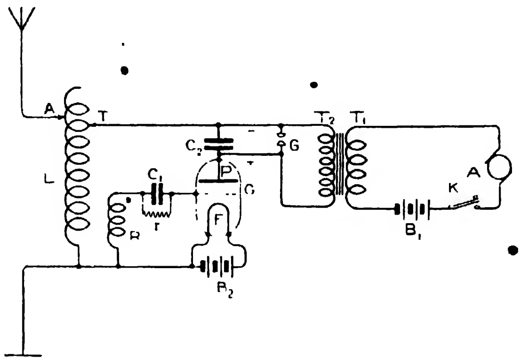


FIG. 258.—Use of an induction coil fitted with a rotary interrupter to supply the steady anode voltage.

cannot usually be distinguished from another except by its call letters.

In both Fig. 256 and Fig. 258 a spark gap G is provided. Normally, this gap is too wide to allow a spark to pass when signalling with the key K. If, however, there is something faulty with the set and the current from T_2 is not absorbed in the anode circuit, sparks should pass across G.

Use of Rectified Alternating Current.—As alternating current may easily be stepped up to any desired voltage it is particularly suitable for use on C.W. transmitters. By rectifying the current after it has been stepped up to a suitable voltage we can obtain an almost steady E.M.F., which is then applied to the anode of the transmitting vacuum tube. The use of alternating current becomes necessary on the high-powered C.W. transmitters which use an anode potential of 5,000 volts and upwards, since direct current of this voltage

is not easily obtainable. The advent of the hard vacuum tube has made the rectification of alternating current a simple matter.

Rectifiers may be divided into two classes, half-wave and full-wave. They may also be divided into two further classes,

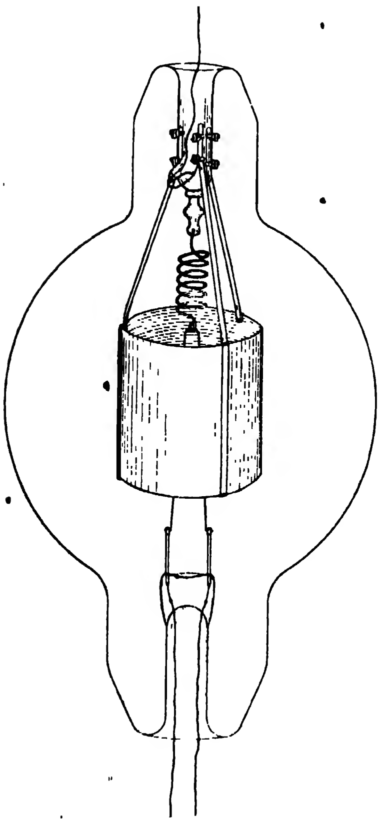


FIG. 259.—A two-electrode valve rectifier (J. Scott-Taggart).

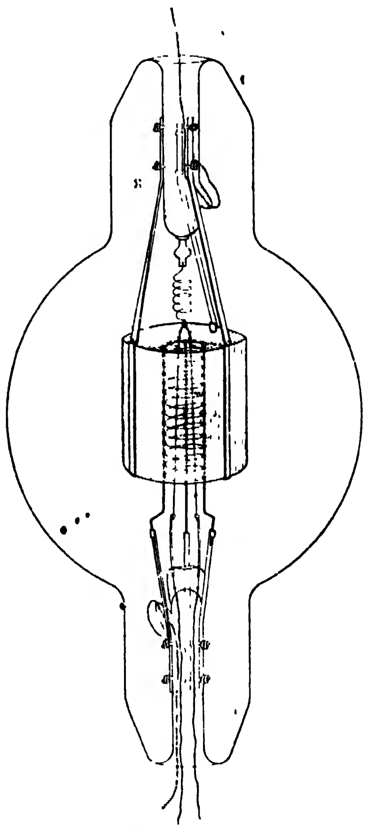


FIG. 260.—A three-electrode transmitting tube.

namely, those using high vacuum bulbs and those in which gas is present.

Half-wave Rectifiers.—This class of rectifier usually consists of a type of Fleming valve in which a heated filament emits electrons which pass to a cold anode. Only when the anode is positive does a current flow. Consequently the

device is very suitable for use as a rectifier of alternating currents. Fig. 259 shows a high power rectifying valve designed by the author for the Edison Swan Electric Company, Ltd. It will be seen that the anode and filament connections are widely spaced so as to prevent external or internal arcing along the surface of the glass. The essential constructional feature is the method of supporting the anode.

The same construction is employed in the three-electrode tubes designed by the author. Fig. 260 is an example given as a matter of interest.

Fig. 261 shows a simple valve rectifier circuit. A filament F is heated to incandescence by the battery B. A rheostat R varies the filament current. An anode P is placed a short distance from the filament. A source A of alternating current is connected across the anode and filament of the valve. Two output terminals Y and Z are included in the anode circuit of the valve, the resistance L representing the load or external circuit in which the rectified current is to be used. The condenser C is charged up by the unidirectional impulses passed by the valve.

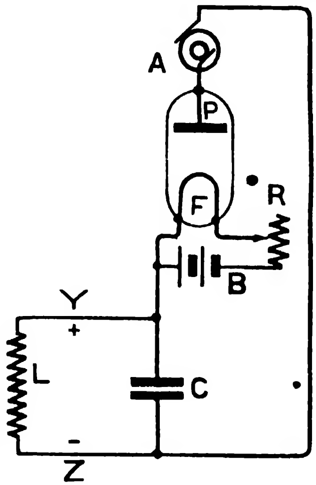


FIG. 261.—Vacuum tube rectifier of alternating current

Let us see the effect of a complete alternation. The alternating current first makes the anode positive and the filament negative with respect to it. Electrons emitted by F flow to the anode and set up an anode current which passes through the external circuit L from Y to Z, or, more correctly, charges up the condenser C, from which is drawn the current which flows through L. Since the electron current flows from Y to Z, the terminal Z is positive and the terminal Y is negative. The filament of the rectifying valve is now at a high positive potential compared to Y, and the accumulator B and the rectifier should be very carefully insulated from the earth.

If now the second half-alternation affects the anode, the latter will become negative and no anode current will flow

through L. The current through L is consequently unidirectional and only flows when the positive half-cycle affects the anode. This form of rectification is known as *half-wave* rectification and the condition of affairs is demonstrated graphically by Fig. 262. The top line shows the alternating

A C.

Rectified A C

FIG. 262.—Showing graphically effect of Fig. 261.

current supplied to the rectifier. The second line shows the flow of current into the condenser C, or through L if there is no condenser C.

The amount of current supplied by one of these rectifiers will depend upon the amount of current which can pass between filament and anode. This will depend on :—

(1) The voltage on the anode.

(2) The filament current.

We see this more clearly by referring to the anode-voltage—anode-current curve of Fig. 27 and the text connected with it. We saw that the anode current is limited first by the filament current and then by the anode voltage. We can consequently vary the current supplied by the rectifier by altering the temperature of the filament by means of R. This presumes that the alternating voltage is sufficient to produce saturation. If the anode is given a voltage of 1,000 by the positive half-alternation and 500 volts produces saturation, we are obviously using an unnecessarily high anode voltage and the rectified current will have a flat-topped waveform.

The resistance of the rectifying valve will usually depend on the value of R since the rheostat regulates the current passing through the valve. Consequently the voltage supplied to the external circuit L will depend on the value of R. The current taken up by L is of course limited by the current through the rectifying valve.

Students sometimes fail to understand why the filament of the rectifier is connected to the positive terminal of the external circuit, when clearly it is made negative by the alter-

nator A. The problem is simplified by considering ALFPA as a simple circuit containing two resistances, one being L and the other the path FP of the valve. Since P is at a higher potential than F there is a drop of potential all along the circuit. The anode is positive relative to the filament. The filament F is positive relative to the terminal Z. The terminal Z is positive relative to Y, and so on. Consequently, though the filament is negative with respect to the anode it is *positive* compared to the end Y of the external resistance.

Dushman's Rectifiers.—We have earlier on discussed the Kenotron rectifier developed by the General Electric Company of U.S.A. Saul Dushman of that company has described in British Patent 100104 (Feb. 20 15), several forms of rectifiers for use up to 100,000 volts. In one form, the anode consists of two plates mounted on either side of a filament cathode. The two plates are electrically connected and have an opposing electrostatic attraction on the filament. Another form is the usual cylindrical anode through the centre of which passes the filament. Still another design consists of a cup-shaped anode and a cathode in the form of a short spiral projecting centrally into the cup-shaped anode.

The following particulars of manufacture will be of interest. The envelope (or glass bulb) is given a preliminary exhaust and baking as in the manufacture of incandescent lamps, the last stages of evacuation being preferably carried out by means of a Gaede molecular pump. When the space within the envelope has been exhausted to a pressure of approximately 0·000001 millimetre, the filament is heated to incandescence and a potential of about 2,000 to 3,000 volts is applied between filament and anode, producing an electron discharge across the vacuum and thereby disengaging any gas occluded by the anode. The evacuation is meanwhile continued to remove this gas. Care should be exercised to discontinue the electron discharge if the liberation of the gas becomes great enough to cause the appearance of a blue glow in the tube as this indicates positive ionisation which, if continued, will harmfully affect the cathode filament.

Further particulars about Kenotron rectifiers are given by S. Dushman in the *General Electric Review* for March, 1915.*

It should be noted that if the anode becomes too hot through electron bombardment, rectification tends to become

* See also abstract in *Electrician*, May 28, 1915.

imperfect. If the anode becomes incandescent it will emit electrons itself and the rectifier will conduct both ways, the valve action being lost or partially lost. Most rectifiers are designed so that the anode or plate may be conveniently cooled. Dushman states that about 10 watts per square centimetre of anode area is permissible, corresponding to a temperature of about 1600° K. The present author considers that rectifiers designed for practical high-power transmission should not operate at more than 5 watts per square centimetre.

Meikle's Rectifier.—G. S. Meikle and the G.E.C. (U.S.A.) have described in British Patent 5557/15 (April 13/15), a rectifier which is suitable for use with alternating currents over a current and voltage range comparable to the capacity of a mercury arc rectifier. It differs from devices in which the two electrodes are mounted in a highly evacuated envelope, in that an inert gas such as argon at a considerable pressure fills the bulb. Moreover, an arc is set up inside the valve. Several amperes may be obtained from these rectifiers, which are useful for charging accumulators. They are thus somewhat outside the scope of this work. An interesting feature in this class of rectifier is that its resistance is low, the voltage drop across the valve being only 1 to 2 volts, whereas in the kenotron type of rectifier the voltage drop is very considerable on account of the high resistance of the valve.

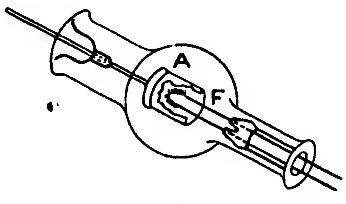


FIG. 263.—Form of Meikle's half-wave rectifier.

A typical form of a half-wave rectifier is shown in Fig. 263. A portion of the anode A is cut away to show the filamentary cathode F. Various inert gases may be introduced into the rectifier; argon, however, appears to be the best. The pressure of the gas may be anything from one millimetre to an atmosphere. Lower pressures of gas cause disintegration of the filament. In order further to protect the filament special shields have been designed and are described in British Patent 5741/15, dated three days later. The filament is heated to incandescence (about 2,000° Centigrade). The anode should be large enough to prevent heating beyond

727° C. The arc is started by the electron emission of the filament but will usually maintain itself even if the filament current is switched off. During evacuation of the bulb gas is removed from the anode by strongly heating it by electron bombardment, and electro-negative gases such as water vapour, oxygen or chlorine are carefully excluded. This class of rectifier, although unsuitable for the rectification of high voltages, has been described here as a subject of interest in connection with rectifiers.

Example of Use of Single-wave Rectifier.—The most useful form of rectifier for small powers is the ordinary hard valve containing an anode and filament. A three-electrode vacuum tube may be used if the anode and grid are connected together. A suitable small power rectifier circuit is shown in Fig. 264. It is composed of a small valve and an induction coil, the secondary of which is connected in the anode circuit of the valve. The induction coil, on pressing the key K, delivers semi-alternating current to the valve, and the battery B_2 is so connected that the maximum pulse (at the "break") of E.M.F. makes the anode P positive. The valve rectifies the semi-alternating current and the rectified pulses, which are always in the same direction, charge up the condenser C of about 1 mfd. capacity. This condenser acts as a store from which direct current may be drawn to feed the anode circuit of the transmitting vacuum tube. The condenser is always kept charged by the small pulses of direct current which do not directly feed the external circuit. The result is that the current drawn from C is almost steady and not pulsatory as was largely the case in the Fig. 256 arrangement. The small rectified pulses are, however, superimposed on the steady current drawn from C and produce a slight ripple on the voltage applied to the C.W. transmitting valve. Experiment shows that this ripple is only about 3 per cent. of the voltage. The signals from a C.W. set using a rectifier of this type are little

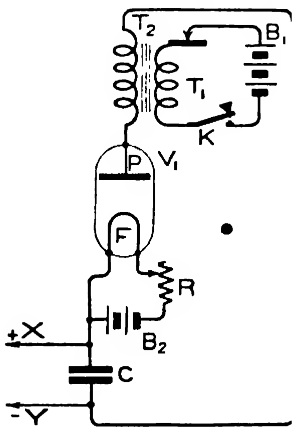


FIG. 264.—Use of valve as rectifier of alternating current supplied by an induction coil.

different from those of a pure C.W. transmitter, particularly if the frequency of the ripple is about 1,000.

Use of Half-wave Rectifier with A.C. Supply.—Fig. 265 shows a complete C.W. transmitter in which the voltage applied to the anode is obtained from a half-wave rectifier working on alternating current from the mains. The alternating current (of, say, 200 volts) is stepped up to about 1,000 or more volts by the transformer T_3T_4. The high voltage across T_4 is applied to the rectifying valve V_1. The rectified current charges the condenser C_1 which acts as the source of anode E.M.F. for the transmitting vacuum tube to the left of the figure. The transmitting circuit is of the usual type and requires no explanation.

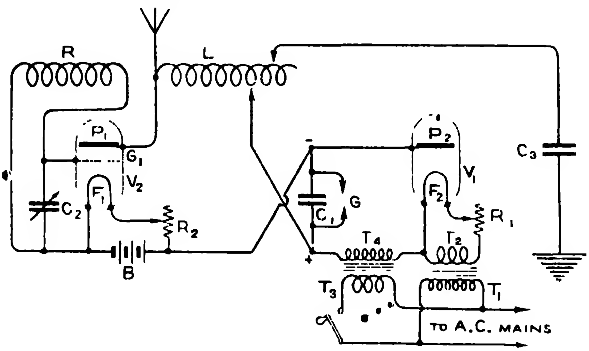


FIG. 265.—Complete C.W. transmitter using rectified alternating current.

A new feature shown is the method of heating the filament of the rectifying valve. This is accomplished by the use of a step-down transformer T_1T_2 which converts the 200 volt alternating current into, say, 8 volt alternating current, which now serves to heat the filament to incandescence. A rheostat R regulates the filament current. Since the voltage across T_2 reverses, the voltage applied to the anode P of the rectifying valve will have 8 volts added to or subtracted from it alternately. This effect, however, is of no importance.

Owing to the high potentials involved, all parts of the transmitting circuit should be very carefully insulated, including the accumulator which heats the filament of the transmitting tube. The windings of the transformers should also be carefully insulated. The condenser C_3 of about 0·001 mfd. capacity is included in the earth lead and prevents the rectifier

being earthed. A safety gap G is connected across C_1 to prevent the breakdown of the latter in the event of the transmitting tube failing to take the current. Signalling is accomplished by means of the key K. The reader will realise that this arrangement is more suitable for higher power transmission.

A New Rectifying Valve.*—The present author has evolved for the Edison Swan Electric Co., Ltd., a special high-power rectifying valve, which has given very good results and which has many advantages over the ordinary type. In the ordinary rectifying tube the anode usually consists of a cylinder of metal surrounding the filament. During operation, the space-charge produced tends to neutralise the effect of the positive potential on the distant anode. Consequently, high anode potentials are necessary. The effect of the space-charge is more marked the greater the diameter of the anode. The anodes of the author's valves have a portion of their metal work constructed close to the filament and between the filament and the main cylindrical anode. The portion thus arranged is of an open-work nature so as largely to neutralise the negative space-charge while allowing the majority of the electrons to pass through the spaces to the main portion of the anode.

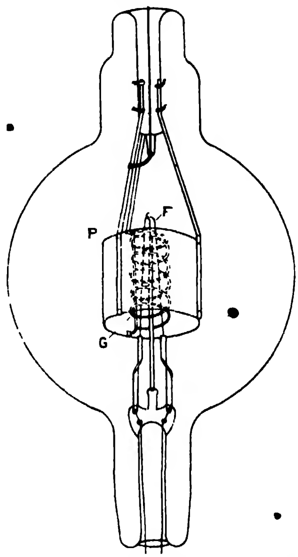


FIG. 266.—A special rectifying valve which passes heavy currents at low voltages. (J. Scott-Taggart.)

The inner portion of the anode, in the larger size valves, takes the form of a spiral of molybdenum wire fixed to the cylinder (Fig. 266). During operation, this spiral is not the same potential as that of the main portion of the anode. Consequently, the space-charge is neutralised and full advantage is taken of the emission from the filament, thus producing an increase in the efficiency of the rectifier. If it is desired to increase the power of a rectifier, the obvious means is to increase the diameter of the anode. This, however, would

* J. Scott-Taggart's British Patent 154364 (Sept. 8/19).

decrease the anode current, unless the anode potentials were increased. By utilising the grid-like structure, the anode current will not be altered, since the effect of increasing the anode diameter will be compensated for by the effect of the grid attachment.

The valve lends itself especially to the rectification of heavy currents at low potentials. A small rectifier of this type passed one ampere at 500 volts. Another very important feature is that the rectified current is very much greater for this valve than any other for a given power dissipation.

Another C.W. Transmitter Employing Half-wave Rectification.—Fig. 267 shows an essentially practical transmitting

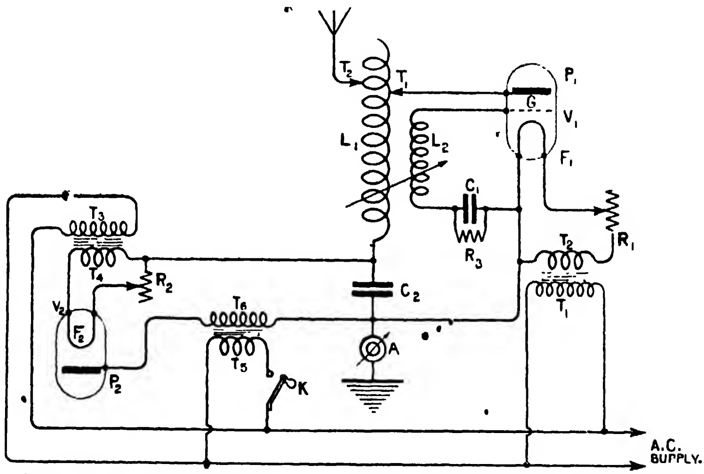


FIG. 267.—A practical C.W. transmitter using half-wave rectifier action.

circuit in which a valve V_2 rectifies the A.C. supplied by the step-up transformer T_5T_6. The condenser C_2 acts as a reservoir for the high potential rectified current and also acts as a by-path for the high-frequency current generated. The filaments of both rectifying and transmitting valves are heated by alternating current.

Full-wave Rectifiers.—When half-wave rectifiers are used the negative half-cycles are not used and are consequently wasted. To remedy this the *full-wave rectifier* has been devised. It is capable of using the energy of both half-cycles, the negative half-cycles being reversed and made to fill up the gaps between the positive half-alternations.

Fig. 268 shows a form of full-wave rectifier designed by the G.E.C. and described in British Patent 5557/15 (April 13/15). The patent itself describes a gas-filled rectifier, but the same class of tube could be used for small-power rectification by exhausting the tube and using it as a kenotron. Two anodes 10 and 9 are placed on either side of a filament 8.

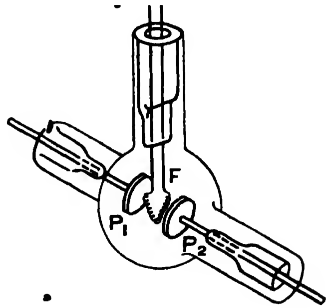


FIG. 268.—Meikle's gas-filled full-wave rectifier.

Fig. 269 shows a circuit used by G. S. Meikle, which utilises the device as a full-wave rectifier. The same class of circuit may be employed when high vacuum valves are used. The secondary winding T_2 of a step-up transformer T_1T_2 is connected as shown to the two plates P_1 and P_2. A tapping M is also taken from the midway point of the winding T_2. Two output terminals Y and Z may be connected in the anode circuit of a C.W. transmitter. The winding T_1 is connected to a source of alternating current, the voltage

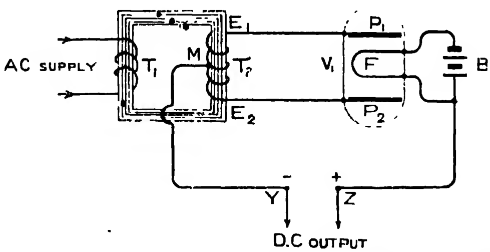


FIG. 269.—Rectifying unit employing full-wave rectification.

of which is stepped up by T_1T_2 and rectified by the double anode valve V_1.

The action of the circuit is as follows: Suppose that a half-cycle of alternating current has been induced in the winding T_2. Let us suppose that the half-alternation has set up an E.M.F. of 2,000 volts across T_2 and that the end E_1 is positive and the end E_2 negative. The point E_1 will be positive while E_2 will be negative with respect to M. Noting now the electrodes to which these points are connected, we see

that the anode P_1 has a potential of +1,000 volts compared to F, while the other anode P_2 has a relative voltage of —1.000. A flow of electrons will consequently take place to the anode P_1 and follow the course FP_1E_1MYZF. The sign of Y and Z will therefore be negative and positive respectively. No current flows to P_2 since it is negative.

Now let us suppose that the next half-alternation comes along and produces an E.M.F. of 2,000 volts across T_1, the end E_2 being positive this time and the end E_1 negative. The anode P_2 is now at a potential 1,000 volts higher than F. An electron current will now flow from F to P_2 through the

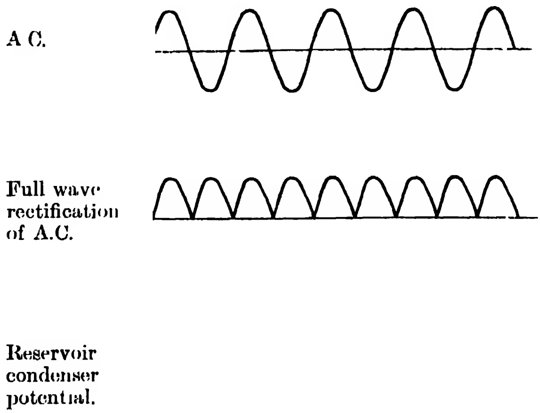


FIG. 270.—Graphic representation of full-wave rectification.

winding E_2M and round *via* Y and Z to the filament. The terminals Y and Z are still negative and positive respectively. This time no electrons flow to P_1 which is relatively negative.

We thus see that the current flowing through the external circuit will be a direct one, and both positive and negative half-alternations will produce a current in the one direction. The graphical representation of the rectification is shown in Fig. 270. The first line shows the alternating current supplied to the rectifier. The second line shows the positive and negative half-alternations acting in the same direction. The third line shows the E.M.F. supplied for use in a C.W. transmitter when a condenser of large capacity is connected across

the output terminals Y and Z. The condenser acts as a reservoir from which direct current is drawn. There will, however, always be a slight ripple R which can be heard by receiving stations within a few miles range. Outside that range the effect is the same as if pure continuous waves were being emitted. The ripple R, it should be noticed, will have a frequency twice that of the alternating current.

In practice it is sometimes more convenient to have two separate coils ME_1 and ME_2 (Fig. 269), instead of one coil T_2 with a midway tapping.

More efficient results are obtained in all electron discharge devices when the anode completely surrounds the filament. The arrangement of Fig. 268 does not allow for this.

The present author has designed a full-wave rectifier,* shown in Fig. 271, in which the filament 1 is surrounded by two cylindrical anodes 6 and 7. The construction shown is suitable for ½ kilowatt valves. This size is the commercial size manufactured by the Edison Swan Electric Company for high-power transmission. The circuit of Fig. 269 may be used with this valve.

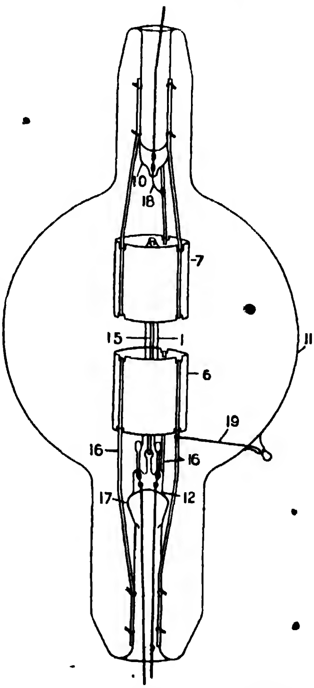


FIG. 271.—Full-wave rectifier (J. Scott-Taggart).

Use of Two Valves for Full-wave Rectification.—Two valves may be used for full-wave rectification. A suitable circuit is shown in Fig. 272. Instead of using two anodes and one filament, two separate valves V_1 and V_2 are used. The filament current of each valve may be varied by means of a rheostat. A condenser C acts as a reservoir to store the rectified current. It will be seen that the valves work alternately. The action of the circuit is exactly the same as that of Fig. 269. Various modifications of this circuit are

* J. Scott-Taggart, British Patent 146708 (June 20/19).

possible. Sometimes a condenser is connected across the winding T_2 to improve the power factor of the transformer. The filaments currents may be regulated by one rheostat.

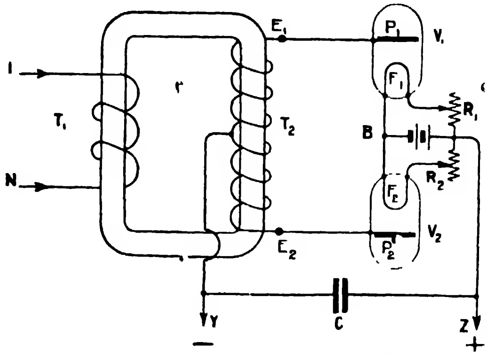


FIG. 272.—A rectifier unit using two valves.

The filaments may be heated by an alternating current obtained from the same source as the current applied to the winding T_1 (compare Fig. 265).

G.E.C. Rectifier Units.—Fig. 273 shows a rectifier unit employed by the General Electric Company (U.S.A.) and designed by W. C. White for use in a wireless telephone which could be operated from the ordinary city alternating current supply A. A primary winding T of an iron-core transformer is connected to the alternating current supply A. Two secondary windings T_1 and T_2 are wound over the primary T. The first has a large number of turns so that the voltage of the alternating current is stepped-up in T_1 to about 800 volts or so, according to the power to be developed by the C.W. transmitter. The other winding T_2 has only a few turns

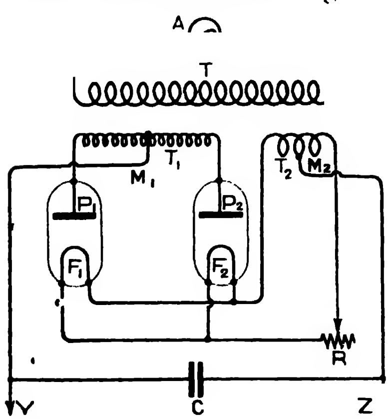


FIG. 273. G.E.C. rectifier for producing high voltages for use in C.W. transmitters.

and is intended to give an alternating current sufficient to heat the filaments of the rectifier valves which are connected in parallel. A resistance R may be included to vary the filament current.* The connection from the filaments is taken from the midway point of T_2 instead of from one side. This arrangement † prevents one end of the filament being overheated by the superimposing of the anode current on the filament current and has been explained earlier on in connection with Fig. 17. The condenser C is of about 6 microfarads capacity and stores the current from the rectifier, which acts exactly as the circuits of Figs. 269 and 272 (except that alternating current is used to heat the filaments). As the condenser C is very large and the current drawn from it is small, the E.M.F. across C will remain constant to all intents and purposes, especially if the frequency of the alternating current is high. The terminals Y, Z are connected to the anode circuit of the C.W. transmitter in the position occupied by an anode battery in the smaller-powered sets. The arrangement shown in Fig. 273 might be varied by using two separate transformers, the primaries of which could be in parallel across the alternating current mains, but this class of transformer is the special design favoured by the G.E.C.

A High-power C.W. Transmitter.—A transmitter may be arranged employing only the alternating current from the mains or from a special small rotary converter.

Fig. 274 shows a C.W. transmitter which is a modification of the circuits used by the G.E.C. for wireless telephony. No method of keying is shown. A primary transformer winding T is provided and supplies alternating current to three secondary windings T_1, T_2, T_3. The windings T_1 and T_3 have only a few turns. The current in T_1 heats the filament of the transmitting vacuum tube, while that in T_3 heats the filaments of the rectifier valves. Connections to the middle points of the windings are taken for the reason explained above.

A second reason which applies to the winding T_1 of the transmitter valve is as follows: If the connection were taken to one end of T_1 and the potential across T_1 were 10 volts, the grid potential would alternately vary from zero to +10 volts according to the direction of the half-alternation.

* Sometimes the filament current is passed through an iron-core choke and varied by movement of the iron-core.

† See British Patent 15448/15 (Nov. 2/15).

Similarly the anode voltage would vary by 10 volts. This is undesirable, and is largely avoided by taking a half-way tapping as shown.

Smoothing out Rectified Current.—The rectified current from a vacuum valve is pulsatory, more especially if only half-wave rectification is employed. This pulsatory variation of the voltage supplied to the anode of the C.W. transmitting tube causes the amplitude of the continuous waves to vary; this "ripple" causes the received signals to be distinctive from the clear notes obtained when pure continuous waves are emitted. Moreover, the ripple causes the waves to be detectable over a considerable range on an ordinary non-heterodyning receiver. Consequently a semi-C.W. station

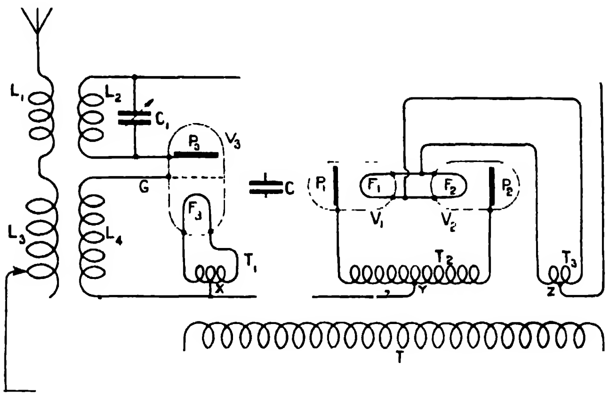


FIG. 274.—Modified G.E.C. continuous-wave transmitter.

causes considerable interference with stations receiving spark signals; this interference is not caused when pure continuous waves are radiated. Another disadvantage of the ripple is that it makes the transmitter largely unsuitable for use as a wireless telephone, which requires perfectly pure waves; the only "ripple" existing should be that produced by the microphone when spoken into, as will be seen later.

To lessen the effect of the ripple we may use full-wave rectification of alternating current having as high a frequency as possible, say 1,000 to 2,000, or even higher. We then charge a large condenser having a capacity of 1 or more microfarads with the rectified current. The E.M.F. across this condenser will be fairly uniform and may be used to energise the anode

circuit of a transmitting vacuum tube. There will, however, still be a slight ripple on the direct current supplied, due to pulsating E.M.F.'s superimposed on the steady current.

These pulsatory E.M.F.'s may be minimised still further by using choke coils in the leads to the rectifier.

A Complete High-power C.W. Transmitter.—Fig. 275 shows a complete C.W. transmitter for long-range work. With quite a small transmitting vacuum tube, such a circuit will transmit almost pure continuous waves over a range of about 300 miles. It will be seen that a separate path through C_2 and L_1 is provided for the high-frequency oscillations, while the steady anode voltage obtained from the rectifier is placed directly across anode and filament. The reader is thoroughly acquainted with this method of connection. The following particulars will be of interest.

Rectifier.—Alternating current is supplied to the terminals IN. The current passes through the primary T_1 of a step-down transformer T_1T_2 which supplies a current of about 8 volts E.M.F. to the filament of a rectifying valve similar to that shown in Fig. 271. The resistance R_2 is a rheostat for varying the current supplied to the filament. The transformer T_3T_4 has its primary T_3 across the alternating current supply. A rheostat R_3 is used for varying the current through T_3 and therefore may be used to regulate the power of the transmitter. A tapping-key K is used for signalling purposes. On closing K the rectifier anodes are supplied with the high-voltage produced in T_4. This may be about 1,000 to 1,500 volts. A large condenser C_5 is connected across the filament and the middle point of T_4, which may be wound in two separate coils.

Ripple Eliminator.—Two iron-core choke coils L_5 and L_6 are connected as shown and are intended to prevent the passage of the low-frequency pulsations, while readily allowing the passage of the direct current which flows between filament and anode of the transmitting tube. One choke-coil only could be used if desired. A condenser C_4 of smaller capacity than C_5 is connected as shown.

Transmitter Circuits.—The filament of the transmitting tube is heated by current induced into T_6 by the primary T_5 of a step-down transformer connected to the alternating current supply. The only ripple likely to be produced is that caused by the fluctuations of the filament current varying the electron emission. The filament, however, does not

readily cool, partly due to the vacuum around it, which acts towards it on the principle of a vacuum flask. Before the

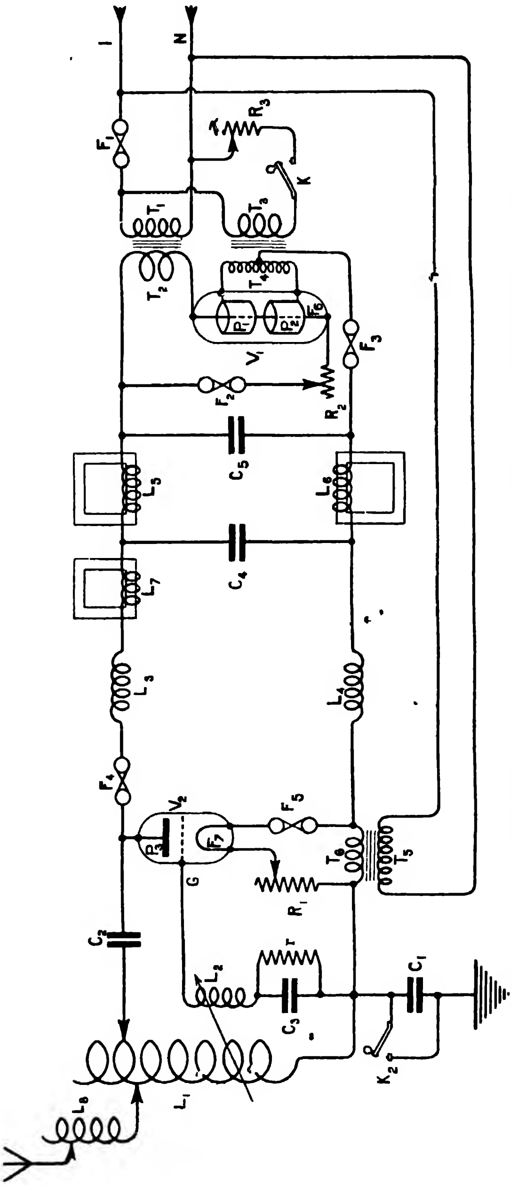


FIG. 275.—A complete high-power C W. transmitting station using a full-wave rectifier.

filament has had time to cool another half-alternation is there to maintain its temperature. Naturally, the higher the frequency of the current applied to the filament the better.

The resistance r (of about 8,000 ohms) shunted by a condenser C_3 (of about 0·002 mfd.) is an arrangement which we have previously discussed. The condenser C_2 (of about (0·0005 mfd.) provides a path for the high-frequency current in the anode circuit. To prevent any radio-frequency current passing through the D.C. anode circuit, two air-core chokes L_3 and L_4 are connected as shown. These allow the direct current to pass while stopping any high-frequency oscillations. An iron-core choke L_7 is also intended to act as an impedance which causes the high-frequency oscillations to take the path C_2L_1. It also minimises still further the ripples on the E.M.F. supplied by the rectifier. It can usually be omitted.

The grid coil L_2 is shown aperiodic and is coupled to L_1 A condenser C_1 might be connected in the earth lead for short wave-lengths, but it is normally shorted. Obviously a variable condenser cannot be conveniently used for tuning the aerial circuit, as the high power used would cause arcing across the plates unless a special condenser were used. If fine tuning is not accomplished on the inductance L_1, a separate variable inductance L_8, included in the aerial circuit, may be used.

Special Remarks.—A fuse F_1 is connected in the A.C. circuit to protect the apparatus. Fuses F_2 and F_5 are connected as shown to protect the filaments from an excessive flow of current. The fuses should "blow" when a current almost sufficient to burn out the filaments passes through them. Fuses F_3 and F_4 are to protect the anode circuits of rectifier and transmitter respectively.

It should be noted that the *negative* side of the rectifier (the middle point of T_4) is ultimately connected to earth. On no account should the filament of the rectifier be connected to earth since it has a high positive potential which makes careful insulation of the rectifier essential. Circuits in which the anode oscillatory circuit is actually part of the D.C. anode circuit (*e.g.* Fig. 265) should have a separate aerial circuit or a stopping condenser in the earth lead in order to insulate the rectifier. Careful insulation of the aerial is now especially necessary.

It should be noted that when the anode oscillatory circuit

is shunted, as in Fig. 275, across the D.C. anode circuit, the aerial is perfectly insulated (by C_2 in our case) from the source of anode voltage. If the aerial were accidentally touched the shock would only be that due to the high-frequency oscillations and not the dangerous steady voltage from the rectifier.

When a motor generator is used to work a transmitter of the type shown in Fig. 275 trouble is liable to be caused by the difference in load when sending on K and when not depressing the key. The generator slows down when the key is depressed and a heavy current is taken by the rectifier. This slowing down causes the current through the filaments of the transmitting and rectifier vacuum tubes to decrease, and the filaments go dim. On releasing K the converter speeds up and the filaments become bright again. If while the key K is depressed the filament resistances R_1 and R_2 be adjusted to give the full current, the raising of the key will be accompanied by an additional increase of current which will blow the fuses or, if the latter are not used, will burn out the filaments. This trouble has been eliminated on some sets by providing shorting contacts on the key which short special resistances permanently included in the filament circuits when the key is depressed. The drop in the voltage supplied to each filament is now compensated for by a lessening of the resistance of the filament circuit. On releasing the key, the extra E.M.F. across the filament does not cause an increased filament current since the extra resistance now comes into the circuit.

Use of Positive Half-cycles of A.C.—We have already indicated that the positive half-cycles of alternating current may be used as the source of plate voltage. Fig. 276 shows a circuit in which alternating current, supplied by A, passes through an auto-transformer T_1 when the key K is closed. A variable tapping S is provided; the whole coil T_1 acts as the primary of the transformer while the portion between S and E_2 acts as the secondary. The arrangement is given in this diagram merely to introduce a very convenient method of varying the power and anode voltage of the transmitter. Maximum power is obtained when S is at E_1. The full voltage of A is now placed across T_2. The coil T_2 might be replaced by a plain resistance but such an arrangement would result in a waste of power.

The alternating current in T_2 is stepped up by the trans-

former T_2T_3 and supplied to the anode circuit of the transmitting vacuum tube through two air-core chokes L_2 and L_3, which are to prevent H.F. current reaching the transformer. The condenser C_2 by-passes this current. The grid-circuit is shown tuned.

The use of alternating current is suggested by Arco and Meissner in British Patent 252/1914, which describes various uses of the vacuum tube. "It is thus convenient to supply the relay by alternating current, since a higher potential can be given in this case (if desired, using a transformer). . . . Generation always takes place in the half period in which there is a positive potential at the anode. In this way trains

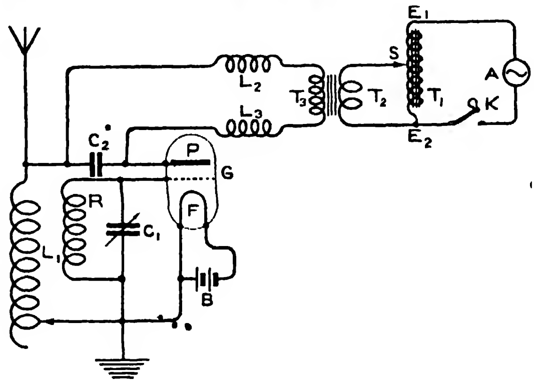


FIG. 276.—C.W. transmitter using positive half-cycles of alternating current.

of oscillations are obtained which are separated by pauses of the length of a half period of the alternating current supply."

We thus see that the "ripple" on the continuous waves emitted will be considerable and the signals will be able to be read on an ordinary damped-wave receiver. The higher the frequency of the A.C. supplied, the more nearly will the signals resemble those obtained with pure C.W. Incidentally half the energy of the alternating current supply is not used.

Use of special Vacuum Tubes to use both Cycles of A.C. for C.W. Transmission.*—Fig. 277 is a diagram of a special vacuum tube designed by the author for transmitting with alternating current in such a way that both half-alternations

* British Patent 146708 (J. Scott-Taggart).

are used. The arrangement is similar to the valve shown in Fig. 271, in that two cylindrical anodes P_1 and P_2 surround a single central filament F. A grid G is placed between the anodes and the filament. Connections are taken from the four electrodes to the outside of the bulb.

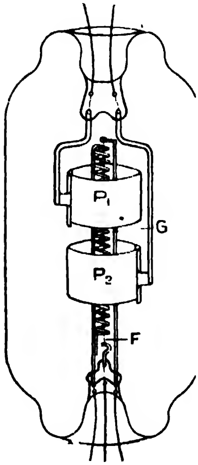


FIG. 277.—Theoretical form of special vacuum tube for using both cycles of A.C. for C.W. transmission (J. Scott-Taggart).

The suitable circuit for use with this tube is shown in Fig. 278. Alternating current feeds the filament through the transformer T_3T_4. Alternating current, stepped-up by the transformer T_1T_2, also feeds the anode circuits of the transmitter. A half-way tapping along T_2 is connected through L_1 to the filament. When a half-alternation is induced in T_2, the anode P_2, say, is given a positive potential relative to the filament F. An electron current consequently flows in the direction $FP_2L_4T_2L_5L_1F$ and sets up oscillations in L_1 which are self-supporting. Meanwhile the anode P_1 is negative with respect to F and no current flows to P_1. When, however, the alternating current reverses at the next half-cycle, the anode P_1 becomes positive and a current flows in the circuit $FP_1L_3T_2L_5L_1F$. Continuous oscillations are therefore set up by each half-alternation. The two anodes P_1 and P_2 are used alternatively and consequently, having time to cool, do not get as hot as the anodes of an ordinary vacuum tube. The condensers C_2 and C_3 by-pass H.F. currents.

Another type of tube designed by the author consists of one anode, one grid, and two separately heated filaments. The anode is connected to the middle point of a step-up transformer and the potentials of the filaments are alternately positive and negative with respect to the anode. The arrangement works in a similar manner to the circuit of Fig. 278, but is not so convenient.

Use of Two Valves for A.C. Current Working.—Fig 279 shows a circuit in which two vacuum tubes are used alternately. No new principle is involved. The two condensers C_2 and C_3 act as by-paths for the oscillating current. They

also improve the power factor of the transformer T_1T_2. The tapping M is connected *via* L to the filaments, which are

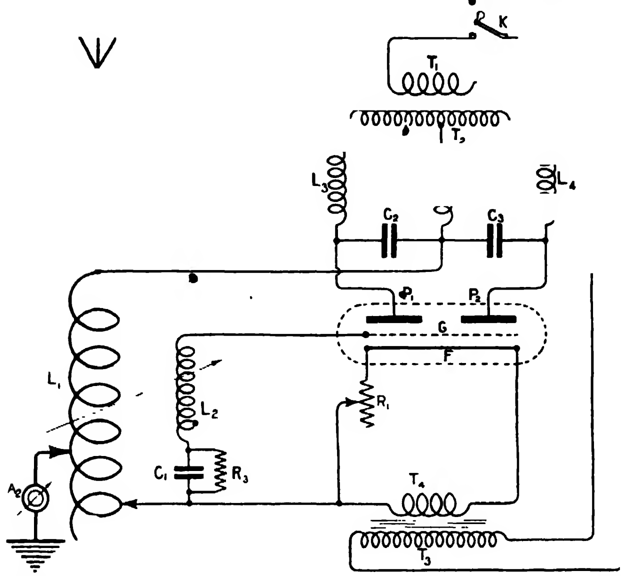


FIG. 278.—C.W. transmitter using alternating current with special vacuum tube (J. Scott-Taggart).

in parallel and heated by alternating current. The anode oscillatory circuit L is now in series with the D.C. anode circuit.

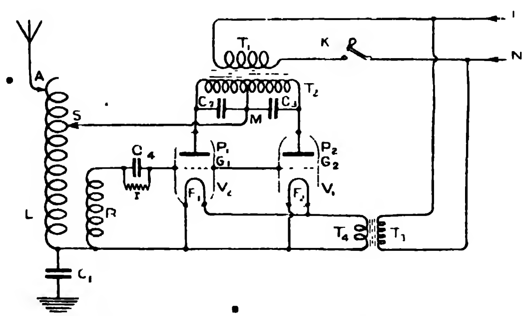


FIG. 279.—Continuous-wave high-power transmitter using both half-cycles of alternating current.

If desired, it could be connected in shunt by disconnecting the lead from the midway point along T_2 and making a new

connection from this point to the filaments. The two condensers C_2 and C_3 now act in turn in a manner comparable to the stopping condenser C of Fig. 253, or the condenser C_2 of Fig. 275. The halves of the winding T_2 act in turn as choke-coils to the H.F. oscillations, and their action is comparable to that of the choke-coil L_2 of Fig. 254.

In the above arrangements it is advisable to connect air-core chokes in the leads to the middle and two ends of T_2. These are not shown in the diagram, but they should preferably be used to prevent the oscillating current from affecting the A.C. circuits.

A G.E.C. Transmitting Circuit.—The General Electric Company (U.S.A.) have patented a vacuum tube transmitter which is illustrated in Fig. 280, which is taken from British Patent 139640 (March 26 19).

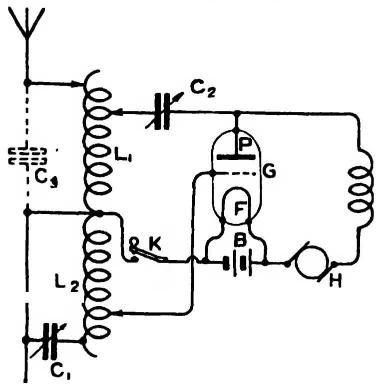


FIG. 280.—A G.E.C. vacuum tube transmitter circuit.

It has been found that the efficiency of a vacuum tube transmitter depends a great deal on the value of the capacity inductance and resistance, of the oscillating circuits. When the anode circuit inductance is also part of the aerial circuit, the capacity and resistance of the system are determined largely by the capacity and resistance of the aerial, and the frequency of the oscillations is then adjusted by varying the inductance. Under such conditions, it will be found that the values of capacity, resistance and inductance thus imposed are not the values which would give maximum output and maximum efficiency for the particular valve used.

The object of this patent is to overcome this disadvantage and provide a system of connections whereby the constants of the oscillating system may be made independent of the antenna constants and may be adjusted to those values which will give the best efficiency of operation.

In Fig. 280, a tapping is taken from about the middle point

on an inductance L_1L_2 to the filament F of a three-electrode tube. A signalling key K is included as shown. A variable tapping is taken from L_1 and connected through the variable condenser C_2 to the anode P. The aerial is connected to another tapping. The source H of anode voltage and a choke-coil Z constitutes the direct current anode circuit, to which the oscillatory circuit is coupled through the condenser C_2 in the usual manner.

The grid G_1 is connected to the lower variable tapping. It will be seen that the inductance L_1 which is included in the anode circuit is also included in the antenna circuit and that the capacity of the antenna, which is indicated in its approximate equivalent by the condenser C_3, shown in dotted lines, will be in shunt to this inductance. As a result, it will be apparent that the capacity of the antenna forms a part of the system in which the oscillations are produced, and since this capacity is fixed, it may not be possible to secure the adjustments of the constants of the system necessary for the best efficiency of operation. To overcome this disadvantage, the inventors compensate for the effect of the antenna capacity by the use of a capacity C_1, which is connected in shunt to the inductance L_2 in the grid circuit, and which preferably has a value approximately equal to the value of the antenna capacity. When the final adjustments are made, the portions L_1 and L_2 of the inductance will preferably have an equal number of turns, and under these conditions the effect of the antenna capacity will be completely neutralised by the condenser C_1 and the adjustment of the system in which the oscillations are produced will be independent of the capacity of the antenna over a wide range of wave-lengths.

The choke-coil Z, which is in series with the generator H, is so designed that it is resonant to the frequency of the oscillations produced, and under these conditions it will act as a substantially infinite impedance to the high-frequency current, while permitting the free passage of direct current. The circuits are applicable to wireless telephone transmitters, and the other figure of the specification is included in the chapter on wireless telephony.

Another de Forest C.W. Transmitter.—In British patent 131361 (June 16/17), Lee de Forest describes another of his continuous-wave transmitters. The diagram accompanying

the specification is reproduced in Fig. 281. The direct anode current circuit includes an impedance Z_2 and an inductance Z_1 and a D.C. generator H. According to the inventor, "the inductance Z_1 is without an iron core, and serves as inertia element in the generation of electrical oscillations. This coil permits high-frequency current to pass through. The impedance coil Z_2 stabilises the direct current in the portion of the circuit in which it is inserted and prevents sudden charges or surges from rendering the system inoperative." The high resistance r shunted by the condenser C_3 appears to carry out the usual functions.

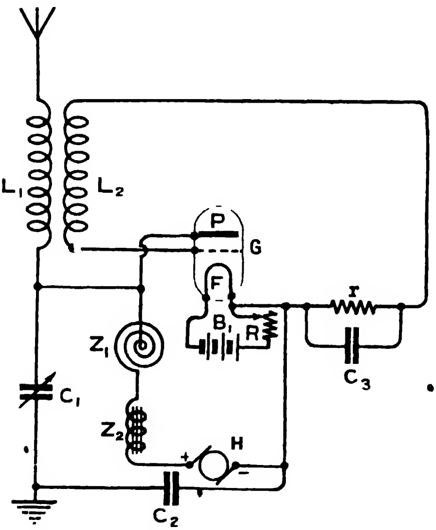


FIG. 281.—Another de Forest circuit.

Although no explanation of the operation of the circuit is given, yet it would appear that the aerial system L_1C_1 constitutes an oscillatory anode circuit coupled to a separate direct-current anode circuit PZ_1Z_2HF, by means of a stopping condenser C_2. The grid oscillatory circuit is coupled to this anode oscillatory circuit to produce self-oscillation. For signalling purposes a key connected in series with the high resistance r.

Multiplex Wireless Telegraphy.—In British Patent 132562 (June 24 18), the Western Electric Co. (U.S.A.) describe an important system of communication employing continuous waves, in which a carrier wave is modulated by several separate signalling waves. At the receiving station the various modulating signals are resolved and separated. By this system several messages may be sent at the same time with one carrier wave. The patent specification shows a transmitting and a receiving circuit, in both of which three-electrode tubes are employed.

Two C.W. Transmitters employing Special Keying Arrangements.—We have already seen how a tapping key may be included in the aerial circuit of a continuous wave transmitter. In Fig. 282 is shown a small-power C.W. transmitter in which a tapping-key K not only makes and breaks the aerial circuit but also the anode circuit. Sparking is very liable to take place and the gap between the electrodes of the key should be wide. The key will control about 60 watts, two vacuum tubes of the French, R, ES_4, or V.T. (U.S.A.) type being employed. The battery H gives about

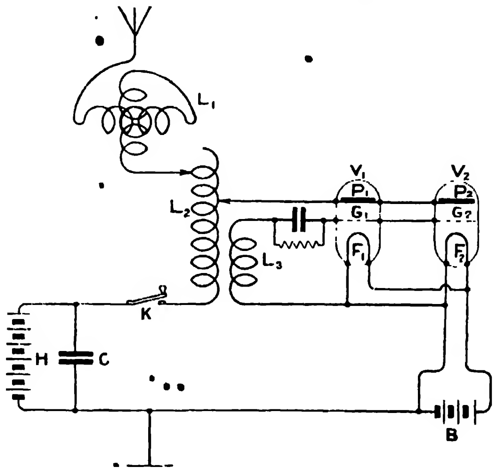


FIG. 282.—A small power transmitter, showing a special system of keying.

800 volts. The negative side of the 6-volt accumulator B is connected to earth. The grid oscillatory circuit is aperiodic. A variometer is included in the aerial circuit for fine tuning. The position of the key is to be noted.

Another C.W. transmitter capable of dealing with ½ K.W. is illustrated in Fig. 283 and is the circuit employed by Marconi's Wireless Telegraph Co., Ltd., in their ½ K.W. cabinet set. The aerial circuit contains a variometer L_1, an aerial tuning inductance L_2, and a fixed retroactor coil L_3, to which is coupled a grid circuit coil L_4. The direct current supplied to the anode circuit is obtained from a rectifier consisting of a two-electrode valve and a ripple smoother consisting of the two condensers C_3 and C_4 and the choke coil Z. The source

of power is a rotary converter or motor generator giving 85 volts at 150 cycles. The transormer T_1T_2 supplies alternating current at 5.000 volts to the rectifying valve V_1, the filament of which is supplied with alternating current at 10 volts by the step-down transformer T_3T_4. The filament of the former valve V_2 is also heated by 10 volt alternating current supplied by the step-down transformer T_5T_6. The direct current anode circuit is separate from the aerial circuit, the coupling being effected by means of the fixed condenser C_2. An inductance L_5 prevents oscillatory current from passing into the rectifier.

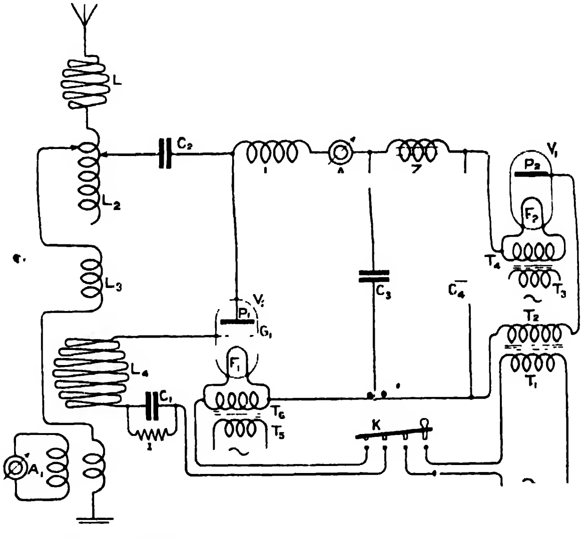


FIG. 283.—A Marconi ½ K.W. continuous-wave transmitter.

A milliammeter A_2 measures the direct current in the anode circuit, and an aerial ammeter A_1 measures the aerial current. It will be noticed that the aerial ammeter is in a separate circuit coupled to the aerial circuit. The range of the set when working on an aerial 100 ft. high and 220 ft. long to a 7-valve receiver is about 350 miles by day. The set may be used for wireless telephone and tonic train transmission, and the reader is referred to the chapter on Wireless Telephony for further details. Signalling is accomplished by means of the key K, which closes both the grid oscillatory circuit and the main supply circuit to the transformer T_1T_2. It will be readily understood that even when the main supply is

cut off, a circuit of this type will oscillate for a moment longer on account of the current from the charged rectifier condenser, unless one of the oscillatory circuits is broken.

Amplifier Transmitter Circuits.—As we have previously foreshadowed, a very obvious development of the amplifying action of a vacuum tube is to use it in C.W. transmitting circuits. A source of oscillations applies the H.F. potentials to the grid of a power amplifier whose output circuit is coupled to the aerial circuit. This class of circuit enables us to use all kinds of vacuum tube oscillators, including those not adapted for high-power work except by taking advantage of amplifier circuits. Several such circuits are given in the chapter on wireless telephony.

CHAPTER XII.

Vacuum Tube Oscillators, Wave-meters, Capacity Meters and other Measuring Instruments.

The Measurement of Continuous Waves.*– An ordinary wavemeter designed to measure damped waves is of very little use for measuring the length of undamped waves, though it may be used when no more accurate instrument is available. The crystal detector of an ordinary wavemeter is capable of rectifying continuous oscillations, but unless they are broken up in some manner nothing will be heard in the telephones except the initial click when the stream of continuous waves commences. When the oscillations are fairly strong a faint hissing or breathing noise is heard when the wavemeter is correctly tuned. If, however, the waves are broken up into trains, *each train will be rectified*, and will produce a click at its commencement and a click at its completion. The loudness of these clicks depends on the energy in the oscillatory circuit of the wavemeter. This will be at a maximum when the circuit is tuned to the exact wave-length of the waves to be measured.

Here, then, we have one means of measuring the length of continuous waves. In practice the stream of continuous waves may be broken up by rapidly sending dots on the key. The wave-length is determined by turning the condenser of the wavemeter until the clicks are heard loudest in the telephone receivers.

This method, however, is obviously unsuitable for accurate work. The stream of waves might with advantage be broken up by mechanical means, so as to produce a buzz in the telephones. Or, better still, the rectified current passing through the 'phones might be split up to obtain the same effect.

Whichever method is adopted, no accurate results can be obtained, owing to the difficulty of determining exactly the

* J. Scott-Taggart, *Wireless World*, V., No. 55, p. 489 (Oct., 1917), also *Electrician*, LXXXIII, 10.

loudest point. The personal element is therefore a principal cause of error.

It is a well-known fact that the human ear finds it far easier to differentiate between two note frequencies than between two different strengths of a note. In the second method, described below, the personal element consists of being able to tell the lowest note heard in the telephones, and not even a comparatively large personal error will practically effect the accuracy of the result.

This second method, which is by far the more scientific and accurate, depends for its action upon the interference effect produced by a stream of continuous oscillations superimposed on another stream of continuous oscillations of a different frequency. The wave-meter used for this purpose is a miniature and very simple form of valve instrument for receiving continuous waves. A suitable design is shown in Fig. 284.*

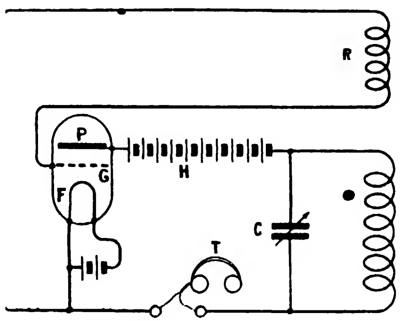


FIG. 284.—Wave-meter using a retroactor coil.

The anode P of a valve is connected to the positive of a battery H of small dry cells giving a potential difference across its ends of about 15 volts. The negative side of this battery is connected to an inductance coil L, which has in parallel with it a variable condenser C, calibrated in wave-lengths. The value of this inductance is such that with the condenser at zero it will oscillate at the minimum frequency desired. The condenser has a value which will enable the circuit to be adjusted between the limits desired, say, for example, from 600 meters to 1600 meters. The telephones used are of low resistance. The retroactor coil R is aperiodic, and should have about the same inductance as the coil L. The coupling between the coil R and the inductance L is comparatively tight, so that when connected up the whole system will oscillate, generating feeble continuous waves. This, of course,

* For general purposes it is preferable to have H next to the filament instead of the anode P.

will only happen when the retroactor coil is the right way round relative to the other coil. Experiment will show which way round the retroactor coil should be placed.

A wave-meter with the connections given above may be used for a variety of purposes. As it generates continuous waves of a frequency varying with the value of the condenser, it can be used as a sending wave-meter as well as a receiving wave-meter without making the slightest alteration whatever to the circuits.

Let us, however, for the time being, consider only its use as a measurer of the length of continuous waves. Suppose the instrument is brought up to a set which is sending out waves of, say, 800 metres length. These waves will have an interference effect on the oscillations already taking place in the wave-meter. If the wave-meter is set to, say, 750 metres, the system will be oscillating at a frequency of 400,000. When the wave-meter receives the 800-metre continuous waves, oscillations of 375,500 frequency are set up in addition. These two sets of oscillations, superimposed upon each other, will produce a resultant oscillating current, with beats when the two sets of oscillations are momentarily assisting one another. The frequency of these beats will be equal to the difference of the two separate frequencies, and will in the present case be 25,000.

The valve is also acting as a detector in addition to generating oscillations. The beats, therefore, are rectified, and will produce in the telephone receivers a note having a frequency equal to the beat frequency. This note, to be audible to the human ear, must be below a frequency of about 14,000.* It is obvious then that if the wave-meter be set to 750 metres nothing whatever will be heard in the 'phones. Only when the wave-meter condenser is turned round till 770 metres is reached will anything at all be heard in the ear pieces, and then only an exceptionally high note. As the wave-meter is turned nearer to 800 metres—*i.e.* as the two frequencies approach each other—the note in the telephones gradually gets lower and lower till at 800 metres nothing whatever is heard. The two frequencies, local and superimposed, are now identical, and, whether in phase or not, produce resultant oscillations of constant amplitude, and which therefore are unable to affect the telephones even when rectified.

* This figure is the ultimate limit. A more practical value is 3,000.

As the condenser of the wave-meter is gradually turned further round to wave-lengths higher, this time, than ·800 metres, beats begin to be formed, and a low note is heard which gradually gets higher as the condenser is turned, until at about 830 metres the note gets so high that the ear can no longer hear it.

It is therefore seen that if the wave-meter is over 30 metres out on either side nothing at all will be heard.

From the above consideration it will be seen that, in order to measure waves of unknown length, it is only necessary to turn the wave-meter condenser round until a "chirp" is heard. This "chirp" when analysed consists, as described above, of a high note, gradually getting lower till nothing is heard, and then rising from a low note to a high one again. The wave-meter is adjusted to the middle part, so that whichever way the condenser is turned a note will be heard which rises higher and higher. The reading on the wave-meter will now give the wave-length required.

It has been supposed that the condenser of the wave-meter has been calibrated in wave-lengths. This calibration should not present any difficulties. An ordinary spark wave-meter of known accuracy, should be set at known wave-lengths. The oscillating wave-meter is brought near, and will "heterodyne" the damped waves. The condenser is turned backwards or forwards until a buzz is heard in the telephones. The loudest part of this buzz is found, and the condenser is marked at that point with the wave-length as given on the "spark" wave-meter. In a similar manner the whole scale is calibrated at intervals of, say, 25 metres.

Once such a standard wave-meter has been calibrated, any number of similar wave-meters may be calibrated from it with very great accuracy—in fact, to within a few metres. All that is required is to bring the uncalibrated wave-meter near, but not too near, to the standard one. Set the standard wave-meter to, say, 600 metres, then move the condenser of the uncalibrated wave-meter round until a chirp is heard. Adjust it more carefully to the middle of the chirp so that on taking the hand away nothing is heard in the telephone receivers. Then mark the condenser with the same wave-length as that on the standard wave-meter. This procedure is repeated every 25 metres until the condenser has been completely calibrated.

It will be noticed that the capacity of the hand will cause an inaccuracy of a metre or two in the wave-length denoted unless the hand is taken right away. For a similar reason there should be no earthed objects in the vicinity of the wave-meters. A metal-foil casing round the wave-meter, preferably earthed, will overcome largely these capacity effects.

So far the measurement of transmitted continuous waves has only been considered. It is just as important to know the wave-length on which a distant continuous-wave station is sending. In order to do this the receiving apparatus, which is pre-supposed to depend upon an oscillating valve for its action, is tuned until the distant station is heard. The note frequency of the received signals may be varied at will, and for the present purpose the apparatus should be tuned so that nothing is audible in the receivers, and yet, if the tuning be varied either way, the distant station will be heard. When this condition is obtained the frequency of the local oscillations generated by the valve is equal to the frequency of the incoming waves. If a wave-meter be now brought near to the receiving instrument the feeble waves emitted by the latter can be accurately measured in exactly the same manner as described above. The length of these waves is the same as that of the waves from the distant station.

Further Notes.—So far the measurement of continuous waves has been considered from a more or less theoretical point of view, without more than a passing reference to some of the difficulties encountered in the practical working of an oscillating wave-meter. These difficulties are worthy of consideration and can be overcome by suitable modifications of design based on experimental results.

The circuit described above, though giving excellent results, can be profitably simplified without detracting from its efficiency as a receiver and generator of undamped oscillations. From the first circuit (reproduced in Fig. 284) it is seen that sustained oscillations are produced by having a separate retroactor coil coupled to another coil of variable wave-length. This coupling is, of course, fixed and should not be altered, as a variation of coupling also produces a variation of wave-length to a certain extent.

For practical purposes, then, it is really unnecessary to have two separately wound coils, which would entail extra care in construction. The same principle may be applied in a more

practical manner than shown in Fig. 284 by using a single coil wound with fine insulated wire and having a tapping taken from about half-way. Fig. 285, which illustrates this, also shows the modifications necessary to make the circuit similar to that given in the first diagram. The telephone receivers and anode battery are still in the anode circuit, and the grid circuit consists of the lower half of the coil, the half-way tapping going to the positive side of the six-volt accumulator and the extra lower end of the coil being connected to the grid of the vacuum tube.

By revising the circuit of Fig. 284 in this manner the construction of the wave-meter becomes simpler. In the original circuit it was necessary to take care that the two coils were wound correctly relative to each other, as otherwise there would be an opposing effect by the reaction coil, and the system would refuse to oscillate. By using a single coil, with a tapping half-way, as shown in the second diagram, the general construction becomes simpler and it is impossible to have the coils reversed. The circuit can therefore be connected up without previous trial, and is certain to oscillate.

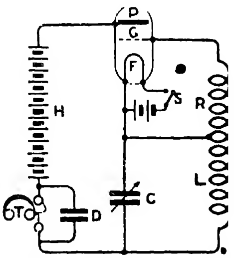


FIG. 285.—Wave-meter using a single coil

It is not intended to give any detailed particulars regarding the actual number of turns of wire, etc., or any such minor points of construction. They will vary according to individual requirements, and the acutal construction presents no difficulties. It will not, however, be out of place to draw attention to one or two details of general design which will result in an efficient measurer of continuous waves.

The retroactor coil R in Fig. 283, as in Fig. 284, is of fixed inductance, having a value about equal to the portion of the coil included in the anode circuit—*i.e.* the lower half. This retroactor coil is aperiodic, and the oscillations which take place in it, when the circuit oscillates, are forced. One end of this coil is connected to the grid of the valve and the other end is joined to the positive side of a six-volt accumulator. The accumulator used need not necessarily be a six-volt one, but that is a suitable size. An accumulator of higher

voltage can be used and will require less voltage on the anode to make the valve oscillate. On the other hand, the filaments of most valves at present in use will soon burn out if more than six volts are put across them. A six-volt accumulator is therefore a suitable source of current for heating the filament of the valve.

The anode circuit coil—the lower coil in Fig. 285—is about the same size as the retroactor coil, and has in parallel with it a variable condenser C. One side of this condenser is connected to the same side of the accumulator as the grid circuit coil. The other side of the condenser is connected to a pair of low resistance 'phones. The other side of the telephones are connected to the negative side of the anode battery, the positive of which is connected directly to the anode of the valve.

The telephones are of the low-resistance type, although high-resistance 'phones can be successfully used. Changing from high-resistance 'phones to those of low resistance causes an appreciable change of wave-length, however. High-resistance telephones give the anode oscillatory circuit a slightly greater wave-length. To obviate this effect on wave-length a small fixed condenser D, of about ·002 mfd., is placed across the telephone terminals. This condenser does not affect tuning, but offers an easier path for oscillations than through the telephones, which, even when of the low-resistance type, possess considerable impedance, which tends to prevent the valve oscillating. Comparison of results obtained with and without the condenser shows that the oscillations are appreciably feebler without the condenser.

The anode battery in Fig. 285 may consist of four or five ordinary flash-lamp batteries, giving a voltage of about 20 volts. This voltage is ample to give fairly strong oscillations. The valve, in fact, will easily oscillate on 10 volts, and even 6 volts. If 8 volts are used for lighting the filament it will oscillate on about 3 volts. The battery,* however, especially if it consists of small cells, should be of sufficient voltage to produce fairly strong oscillations, to allow for a drop of voltage after it has been used for some time. There is another and more important reason, however, for having the oscillations in the wave-meter fairly strong. It has already been stated

* The ES2 valve designed by the author for the Edison Swan Electric Company and the "S" valve will oscillate under certain conditions without an anode battery.

in the previous section that, in addition to receiving continuous waves, the wave-meter also sends out waves of variable length, which can be picked up on any instrument designed for the reception of such waves. Immediately the filament current is switched on by means of the switch S, sustained oscillations are set up which will continue all the time the valve is alight. These oscillations set up continuous waves of a definite length which, though incapable of travelling more than a short distance, are still sufficiently strong to influence a continuous wave receiving instrument when brought within a few yards of it.

An oscillator or wave-meter of even greater ease of production is obtained by connecting the variable condenser C across the whole of the inductance RL instead of across L. No retroactor coil is now used.

Without any alteration to the circuit the wave-meter is also capable of being used as a measurer of received waves, since the valve is oscillating both for sending and receiving, and since the telephone receivers are always in circuit. When, therefore, waves emitted from a transmitting station reach the wave-meter additional oscillations are set up in it which form beats with the feeble local oscillations already taking place.

The relation between the strength of these local oscillations and the strength of the oscillations in the transmitting apparatus has a very important bearing on the correct measurement of continuous waves. Let us only consider for the moment the case of an oscillating wave-meter similar to the one described being used to measure the length of waves emitted by a continuous wave-transmitting station of small power.

If the wave-meter be held at some distance from the transmitter, the oscillations set up in the wave-meter by the transmitter will be of approximately the same strength as those already taking place. The amplitude of these oscillations produced by the transmitter may be varied at will by moving the wave-meter closer to or further away from the transmitter aerial or earth lead.

When the induced oscillations are stronger than the local oscillations much less accurate results are obtained than when the amplitudes are approximately equal. If the wave-meter be held too close to the transmitting instrument, instead of hearing the characteristic chirp when the wave-meter condenser is turned round, only the very high notes are obtained,

and between the two limits is a long silent interval. The length of this silent interval depends upon the relative amplitudes of the superimposed oscillations in the wave-meter. The nearer the wave-meter is to the sending instrument the greater will be the disproportion in amplitude between the local oscillations and those from outside, and therefore the longer will be the silent interval.*

By taking the middle of the silent interval as being the correct wave-length, rough results may be obtained. Such a course, however, is very undesirable, particularly if the silent interval is comparatively long. The wave-meter should always be at such a distance that the peak of the wave seems very sharp, and so that practically no silent interval is heard at all. This result may be obtained either by strengthening the local oscillations in the wave-meter, so as to correspond more with those emitted by the transmitter, or by taking the wave-meter some distance away. This latter method is often inconvenient, as it is desirable that the operator who is working the transmitting set should be able to make the necessary adjustments to send on a certain wave-length, without having to go away from his instruments. In order to obviate such inconvenience the wave-meter should have an anode battery of about 40 volts. It will then be found unnecessary to move the wave-meter away from the set.

In order to obtain the greatest accuracy, however, the best plan is to have the wave-meter and its telephone receivers at a considerable distance from the sending set. The tuning is sharper and no mutual effects between wave-meter and instrument are produced.

Very misleading results are often obtained by having the wave-meter too near the set or aerial. Frequently the fundamental wave is too strong and produces little and sometimes no effect in the telephones. On the other hand, complications arise owing to the weak harmonics generated in addition to the fundamental waves. These harmonics frequently produce much louder chirps than the fundamental waves when the wave-meter is too close to the instrument, and so may give

* Strong continuous oscillations of a frequency near to that of the wave-meter will actually cause the wave-meter to oscillate at the same frequency. No beats are consequently produced, and a long silent interval results. To obtain the most accurate results when measuring waves, it is, perhaps, best not to adjust the wave-meter to the silent interval, but to a fixed beat note compared with a tuning fork.

rise to incorrect assumptions. At a distance, though, these harmonics are too weak to influence the wave-meter, which will then only respond to the real fundamental waves. It would be as well, perhaps, to point out that it is not sufficient to move the wave-meter alone away. The telephone leads and the operator wearing the receivers should also be at some distance from the instrument.

Let us now consider the use of the wave-meter in conjunction with a continuous wave-receiving instrument. The oscillations in both instruments are now more of the same order and the wave-meter may be brought close up to the receiving set without causing complications.

From this it is seen that to measure transmitted waves, the anode battery of the wave-meter should be of higher voltage than is necessary for the other uses of the wave-meter in conjunction with receiving apparatus. A switch may be used if considered desirable to give, say, either 40 volts or 15 volts from the anode battery when the wave-meter is required to receive or send respectively. Such an arrangement is, however, really unnecessary, as an average voltage enables the wave-meter to be used for both purposes.

The actual calibration of the wave-meter, already briefly discussed, presents several difficulties. The variable condenser of Fig. 285 may either be calibrated in actual wave-lengths or in degrees. The latter method is, of course, to be preferred, and when used a card is required similar to that on an ordinary wave-meter, giving the wave-lengths which correspond to the different degrees on the condenser. This system allows of periodical checking of the accuracy of the wave-meter.

The wave-meter is so sensitive that the slightest changes of wave-length can be observed to within a few metres. The slightest alteration of the position of the hand will vary the wave-length to a measurable extent. Even the changing of the valve would necessitate a recalibration of the wave-meter if particularly great accuracy were required. For practical purposes, however, one or two metres make no difference and sufficiently accurate results may be obtained by the use of the wave-meter described.

Another C.W. Wave-meter.—A type of wave-meter which has been used by the Signals Experimental Establishment of the British Army is reproduced in Fig. 286. This circuit is based on the usual principles, except that the telephones

are included in the grid circuit and detection is obtained by the asymmetric variations of the grid currents passing through the telephones T. The inductance L_1 is aperiodic, while the grid oscillatory circuit is tuned by connecting a variable condenser C_1 across L_2. A galvanometer G reading up to about 500 microamperes (such as Weston galvanometer No. 275) is also included in the grid circuit. When the switch K is closed, the filament of the valve lights up and a deflection of about 200 microamperes is immediately registered by the galvanometer if the circuits are oscillating properly. This deflection is due to the oscillations in L_2C_1 being rectified by the Fleming valve action of the grid.

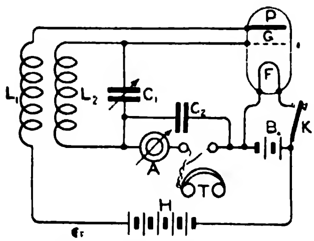


FIG. 286.—C.W. wave-meter with phones in grid circuit.

The wave-meter may be used in a manner similar to the wave-meters previously described. Another method, however, is to tune the condenser C_1 until the galvanometer reading increases to a maximum and then falls back to its normal reading as the condenser is turned further round. At the maximum reading the frequency of the wave-meter oscillations equals the frequency of the oscillations it is desired to measure. In Fig. 286, the accumulator is represented by B, the anode battery by H, and a fixed condenser C_2 is connected across A and T, to by-pass the oscillations. The coils L_1 and L_2 are flat coils mounted on slabs of ebonite. Different slabs, containing different lengths of coils, may be used for different ranges of wave-lengths.

A Buzzing C.W. Wave-meter.—An ingenious wave-meter is illustrated in Fig. 287. It is capable of being used as a transmitting wave-meter of damped as well as continuous waves. Its action depends on a phenomenon described by E. H. Armstrong* and by L. A. Hazeltine.† When a valve possessing a leaky grid condenser commences to oscillate, a negative charge is built up on the grid by the usual valve action. The grid potential will gradually decrease until the operating point approaches the lower bend of the anode current characteristic curve. Under these conditions the valve ceases to

* E. H. Armstrong, *Proc. I.R.E.*, **3**, p. 227.

† L. A. Hazeltine, *Proc. I.R.E.*, **6**, 2, 76 (April, 1917).

oscillate. The negative charge now gradually leaks off the grid and the operating point on the anode curve rises until it reaches a position where self-oscillation recommences. The grid potential now drops again and the process is repeated. In this way the vacuum tube generates groups of oscillations which very much resemble trains of damped waves. The train frequency will depend upon the amplitude of the oscillations produced by the valve and on the rate at which the negative charge can leak off the grid condenser.

The wave-meter is shown in Fig. 287. A double throw-over switch S_1 enables, in the upper position, a leaky grid condenser to be connected in circuit. In the lower position, the switch is shorted and the device acts like the ordinary C.W. wave-meter of Fig. 286. When the switch S_1 is in the upper position the wave-meter will "buzz" in a manner similar to an ordinary "spark" wave-meter. The buzz will be heard in the telephones T, unless the latter are shorted by the switch S_2. If the circuit fails to buzz the filament rheostat R_1 may be readjusted and the switch S_2 changed over rapidly from "C.W." to "buzzer." The note of the buzz may be conveniently varied by altering the adjustment of the filament rheostat.

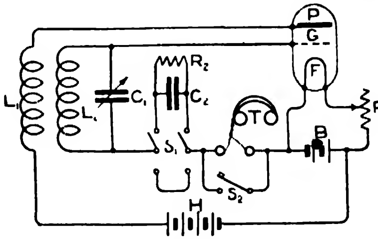


FIG. 287.—Buzzing oscillating wave-meter.

A suitable value of the grid condenser C_2 has been found to be 0·015 mfd. and the resistance R_2 may be 200,000 ohms. This type of wave-meter is of great use as an external heterodyning oscillator. When in the buzzer position, it is a simple matter to tune the receiving circuits to the correct wave-length since the buzzer can be heard on the receiver, whereas if the wave-meter radiated continuous waves the latter would not be detected except for the faint hissing noise. Once the receiving circuit has been tuned, the operator switches S_1 over "C.W." and by a slight retuning of C_1 is able to heterodyne, and so receive, the incoming continuous waves. The telephones T, of course, play no part except when the wave-meter is used to measure waves which are being radiated by another set or station.

The present author has extended this principle of the buzzing wave-meter to all resistance-coupled oscillator circuits such as the "Kallirotron" circuit.

A New Capacity Measurer.—The following description of a new method of measuring capacity is taken from an original article by the present author in the *Electrician* of April 18th, 1919, and produced in December, 1917.*

Most of the present methods of measuring electrical capacity, graduating variable condensers, and performing similar calibrations, are far from simple, or, if simple, are wanting in accuracy and speed of manipulation. The description of an instrument which is capable of rapid and

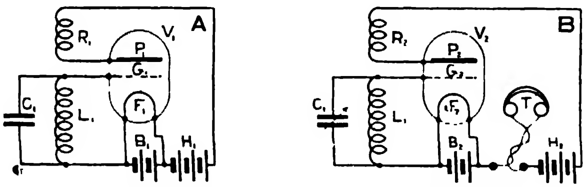


FIG. 288.—A new capacity meter (J. Scott-Taggart).

exceedingly accurate measurement of capacity, suitable for laboratory and commercial use, will therefore be of interest.

The arrangement, which is shown in Fig. 288, depends for its action on the utilisation of the phenomenon of beating effects produced by two sets of superimposed continuous oscillations of slightly different frequencies. If two alternating currents of equal frequency, but out of phase, are superimposed on a circuit, the resultant current will be an alternating one of the same frequency as that of the individual currents and having an amplitude depending upon the difference of phase, the minimum amplitude being obtained when the superimposed currents are 180 degs. out of phase. If, however, two alternating currents of *different* frequency be superimposed on one another, the resultant current will not have a constant amplitude since the phase relationship is continually changing. The amplitude will, at regular intervals, increase and decrease as the two superimposed currents come in and out of phase with one another. The frequency of the increases, or "beats," is equal to the

* British Patent Application 9612/18 (dated June 12/18). This also claims the use of balanced circuits for reception.

difference between the frequencies of the superimposed alternating currents. The same rules apply to continuous oscillations as to alternating currents. Thus, if the frequencies of the component sets of oscillations were 750,000 and 780,000 respectively, the beat frequency would be 30,000 per second. By keeping the frequency of one set of oscillations constant and varying the other set, beats of any desired frequency may be obtained, the beat frequently decreasing as the frequencies of the sets of oscillations approach each other. When these frequencies are equal, no beats are produced, the resultant oscillating current being of constant amplitude.

Let us now consider the effect of passing these currents through a telephone receiver. The individual currents, if passed separately through the receiver, would not affect it, because of their high frequency. Similarly, the resultant current, obtained by superimposing currents of different frequency, would not affect the telephones, since its frequency lies between the two component frequencies; nor will the beats produce any effect. If, however, we rectify the resultant current there will be a unidirectional pulse of current through the telephones for each beat. These pulses at regular intervals will produce a buzzing note whose frequency will be equal to the beat frequency. If this is greater than about 14,000 per second nothing will be heard in the telephones, since the human ear is unable to respond to higher notes than this.

The present arrangement provides a circuit oscillating continuously at a frequency which may be altered by means of a variable condenser; the circuit includes a pair of telephone receivers. Another circuit is arranged which also oscillates continuously at a frequency determined by the capacity of the condenser it is desired to test. This circuit sets up similar oscillations in the first circuit. There will therefore be two superimposed sets of oscillations in the first circuit; beats will be produced which, when rectified, will give a note in the telephones, provided its frequency is within the proper limits. Now let a standard condenser of known capacity be placed in the second circuit, which will then oscillate, say, at a frequency of 400,000. If the variable condenser which controls the frequency of the oscillations in the first circuit be adjusted gradually a high note will be

heard in the telephone receivers when the frequency of the oscillations is about 410,000.

If the condenser be gradually turned round further, the note heard will become lower and lower as the difference between the two separate frequencies becomes less. When the frequency of the first circuit is adjusted to 400,000, no beats are produced and nothing is therefore heard in the telephones. This may be termed the silent period. If the condenser be moved slightly further the frequency of the first circuit falls below 400,000, and a low note is heard which gradually gets higher and higher, as the condenser is turned, until it is no longer audible. To make a condenser of exactly the same capacity as the standard one the silent interval is first obtained with the standard condenser. The other condenser is then substituted and the variable condenser of the first circuit adjusted again to the silent point. The two silent points should exactly coincide when the two capacities have the same value. The minutest difference will be indicated.

Having discussed the underlying principles of the arrangement, let us see how they may be used in practice.

Fig. 288 shows two circuits, A and B, close to each other, each one being a generator of continuous oscillations. The circuit A includes a vacuum tube with filament F, grid G and plate P. The filament is heated by means of a 4-volt battery. In the anode circuit is included an inductance coil R_1 and an anode battery H_1, of about 20 volts. The negative end of this battery is connected to the filament. The grid circuit consists of a coil L_1 one end of which is connected to the grid and the other to the filament. Leads are taken from the end of this coil to two terminals to which the condenser C_1 under test is connected. The coil R_1 is coupled to the coil L_1 so that the whole system oscillates of its own accord. The circuit B is very similar. The coil which corresponds to the coil L_1 is, however, shunted by a variable condenser C_1, graduated in degrees; also the anode circuit contains a pair of telephone receivers. The valve of the B circuit, in addition to oscillating continuously, will also rectify any beats which may be produced in its circuits. Fig. 224 shows the two superimposed currents, the resultant beats, and these beats rectified.

To Graduate the Capacity Meter.—The instrument is not

suitable for measuring absolute capacity. It is therefore necessary first to calibrate it by means of standard condensers. This is done in the following manner: A standard condenser of, say, 0·002 mfd. capacity is connected in the position of C_1 (of circuit A). Suppose this causes the circuit A to oscillate at a frequency of 500,000. By altering the condenser of circuit B the frequency of the oscillations in the B circuit may be altered on either side of 500,000. If these oscillations are of a frequency of 400,000, the beats of 100,000 frequency, though automatically rectified, will not be audible in the telephones T. As the capacity of C_1 (circuit B) is gradually decreased, the frequency of the oscillations in B will increase, and soon a very high note will be heard, owing to the establishment of audible beats which are rectified by the valve. This high note will gradually become lower as the frequency of B approaches the frequency of A, namely, 500,000 per second. When the frequency of B equals that of A, no beats will be produced. An entry should then be made on a calibration chart showing the number of degrees on the variable condenser which are equivalent to 0·002 mfd. A calibration chart is preferable to actually graduating the condenser. On still further increasing the frequency of the oscillations in B a note will be heard again which will rise higher and higher and finally die out. Several different standard condensers should be substituted for the A condenser, and in each case an entry should be made on the chart when the variable condenser is adjusted to such a position that a variation to either side will cause a note to be heard in the telephones. Intermediate graduations are found by drawing a curve. When the instrument is calibrated it may be used for a variety of purposes.

To Measure the Capacity of a Condenser.—The condenser of unknown capacity is connected in place of the A condenser. The variable condenser is varied until a "chirp" is heard in the telephone. The middle of this "chirp" is found, so that a variation to either side would give a note in the telephones. The desired result will be shown by finding the capacity which corresponds to the number of degrees on the variable condenser. This result will be exceedingly accurate. Even the alteration of capacity by placing the hand near will be indicated by hearing a note in the telephones, since the balance of frequencies has been upset. This minute alteration

of capacity might be measured by re-adjusting the variable condenser until the middle of the "chirp" was again heard. The difference between this reading and the previous one would indicate the change of capacity produced by the hand. As this extreme sensitiveness is, in a way, a disadvantage, it is as well, if the circuits be mounted in a box, to enclose the case in a covering of tinfoil connected to earth through a special terminal. It is also as well to adjust the variable condenser by means of a handle a few inches long.

The above arrangement may also be used for comparing inductances, making a large number of inductances all exactly of the same value, etc., by substituting them for the inductance L_1 of circuit A.

The Vacuum Tube as a Voltmeter.—The vacuum tube has on several occasions been used by the author as a very sensitive voltmeter. It is particularly applicable to cases where an electrostatic voltmeter is desired. The E.M.F. it is desired to measure is connected across the grid and filament of a vacuum tube in the anode circuit of which is a milliammeter. The operating point is made such that the grid current is infinitesimal; for example, by using high anode voltages and, if convenient, by applying a negative voltage to the grid. To all intents and purposes the resistance between filament and grid is infinite and the vacuum tube voltmeter if connected across a source of E.M.F. will not cause any drop of potential through absorbing some of the current itself. The action of the grid is purely electrostatic and the device will act in a manner similar to a hypothetical voltmeter of infinite resistance. The voltage may be measured by the variation of anode current, the device having previously been calibrated. Owing to the amplification by the valve, minute variations of voltage may be easily recorded. Several vacuum tubes in series inter-connected by coupling resistances may be used if it is desired to measure very small voltages. The circuit of Fig. 92 might be adapted for this purpose. Another advantage of the arrangement is that the capacity of the grid is very small.

A Method of Testing very High Insulation.—The author has used the vacuum tube as a method of testing insulation. If, say, a condenser is under test, it is connected in the grid circuit of a three-electrode vacuum tube. A battery is connected so that it would make the grid negative if the con-

denser were shorted. The anode current is measured under these conditions, and also when the battery is out of circuit. If the value in the former event is much less than in the latter a leakage in C is indicated by the discrepancy in the readings. A large discrepancy will result even if the leakage be minute. Since the resistance of the vacuum tube between filament and grid is almost infinite, the grid will take up the voltage of the battery unless the insulation of the condenser is perfect.

CHAPTER XIII.

THE VACUUM TUBE IN WIRELESS TELEPHONY.*

IT is proposed in the following chapter to consider the various circuits employing vacuum tubes for the wireless transmission of speech.

General Principles.—It is usual in wireless telephony to send out a steady stream of waves and to vary this stream by means of the sound vibrations of the voice. This steady stream of waves can be obtained by means of various kinds of C.W. generators, those employing vacuum tubes having been described already. The continuous stream, if received on an ordinary non-oscillating detector, will produce no sound whatever. If, however, the steady stream be modulated or varied by means of a microphone so connected in the transmitter circuit as to vary the amplitude of the continuous waves when the microphone is spoken into, the rectified signals at the receiving station will consist of a varying direct current. These variations will actuate a telephone receiver and produce sound waves of exactly the same nature as those produced by the speaker at the transmitting station. The action is somewhat analogous to that of a simple telephone circuit consisting of a microphone, a battery, and a telephone receiver in series. A steady current flows from the battery through the microphone and through the telephone receiver. This steady current produces normally no effect on the telephone receiver. If, however, the microphone be spoken into, its resistance will be varied and the steady current in the circuit will vary in strength, producing a sound in the receiver corresponding to the original speech.

In wireless telephony, a steady stream of waves (usually termed the *carrier wave*) is usually modulated by means of a microphone, the audio-frequency variations generally occurring at rates from 100 to 2,000 per second, the average frequency

* A review of modern methods of radio telephony is given by the author at length in *Wireless Age*, Jan. 1921, *et seq.* Also in *Electrician* of Sept. 10/20.

(sometimes termed the *mean speech frequency*) being about 800 to 1,000 per second. Two general methods of modulation are used at present; either the amplitude of the continuous waves is varied by the microphone, or the wave-length is altered. If the receiving station is tuned to the carrier wave any variations of the wave-length of the latter will produce mistuning and consequently a decrease of response in the receiver depending on the degree of the variation. Sometimes both wave-length and amplitude modulation occur at the same time.

Some of the methods of modulating the continuous stream of waves are :—

(1) Connecting a microphone directly in the earth lead of a C.W. transmitter.

(2) Coupling a microphone circuit to one of the oscillatory circuits of a C.W. transmitter.

(3) Varying the output of a C.W. transmitting vacuum tube by using a microphone to vary the grid potential.

(4) Use of an additional grid whose potential is varied by means of a microphone.

(5) Variation of the anode voltage or anode current of an oscillating transmitting tube by means of a microphone.

(6) Varying the output of an amplifying valve coupled to the aerial. The grid circuit is separately excited by a source of high frequency current and a microphone arrangement affects the output of the amplifier valve in one way or another.

(7) Causing a microphone to vary the resistance of an energy absorbing conductor connected across the aerial circuit or across a circuit coupled to the aerial circuit.

(8) The microphone is made to limit the oscillations in the grid circuit of an oscillator.

(9) The microphone varies the retroaction of an oscillating valve.

Simple Wireless Telephone.—Fig. 289 shows a simple continuous wave transmitter in which a microphone M is connected directly in the earth circuit. The varying resistance of the microphone alters the amplitude of the emitted waves. A switch K is provided. On closing K, the system oscillates and radiates a steady stream of continuous waves.

Fig. 290 shows, in the top line, the steady stream, while the second line shows an example of how the wave-form is altered when speaking into the microphone. In connection with the modulation produced by the human voice, the oscillographs taken by W. Duddell and illustrated in Fig. 291, will be of interest. This figure shows the wave forms of different sounds.

The circuit of Fig. 289 may be modified by coupling an oscillatory circuit which includes a microphone to the inductance L or other inductance in the aerial circuit. These

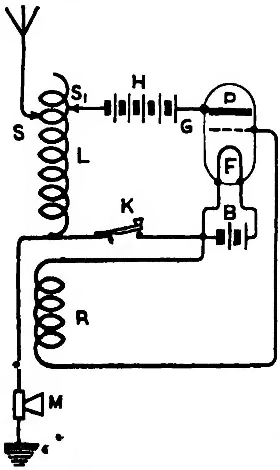


FIG. 289.—Simple wireless telephone with microphone in earth lead.

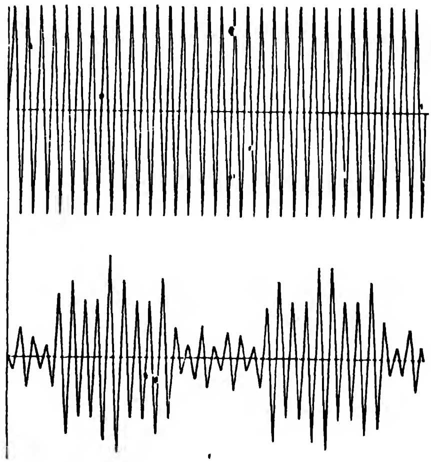


FIG. 290.—High-frequency oscillations modulated by audio frequency variations.

various methods do not appear to have found permanent favour, and many circuits now have for their object the variation of the output of a transmitting tube.

Receiving Wireless Speech.—Wireless speech may be received with an ordinary crystal detector receiving circuit or non-oscillating valve circuit. The various detector-amplifier circuits are all capable of receiving wireless speech, but do not respond to the continuous carrier wave. Heterodyne circuits may also be employed, but this time the carrier wave is heard and gives a steady note whose pitch may be varied by altering the frequency of the local oscillations. It is then usual to make the local frequency equal to the frequency of the carrier wave, so that no beat note is produced,

although speech will be heard since the amplitude of the incoming oscillations varies. Circuits employing this system of reception, have been largely employed by the Western Electric Company (U.S.A.). The present author is inclined

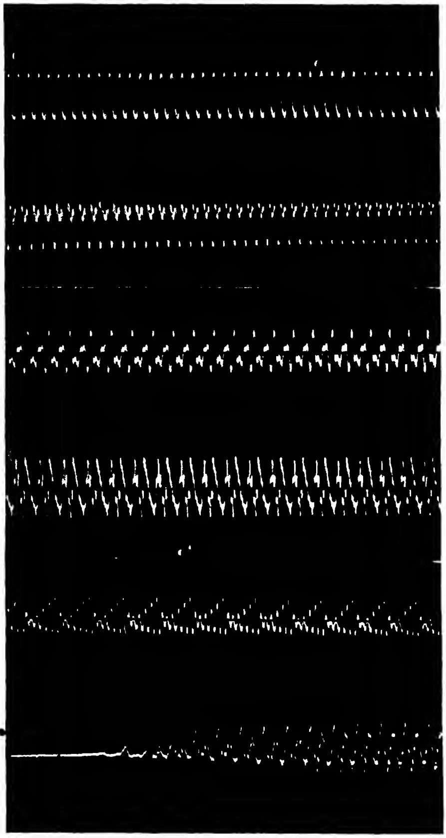


FIG. 291.—Wave-forms of certain speech sounds.

to prefer simple rectification without local oscillations or retroactive amplification, except in special cases.

Round's Wireless Telephone.—In British Patent 13248/14 (May 29/14), Marconi's Wireless Telegraph Co. and H. J. Round describe a wireless telephone circuit which is reproduced in Fig. 292. The action of the circuit appears to be as follows: The high-potential dynamo H supplies a

positive voltage to the anodes of both valves. The first tube acts as an oscillator for generating continuous oscillations in the usual way. An intermediary circuit, consisting of two inductances, a condenser and a microphone M, is coupled to the oscillator. The amplitude of the oscillations in this intermediary circuit is varied by the microphone. The modulated high-frequency oscillations are now induced into the grid circuit of the second vacuum tube and amplified by it. The magnified oscillations in the anode oscillatory circuit are now passed on to the aerial circuit and radiated. Resistances shunted by condensers were as usual connected in the anode circuits and made the action of the valves, which

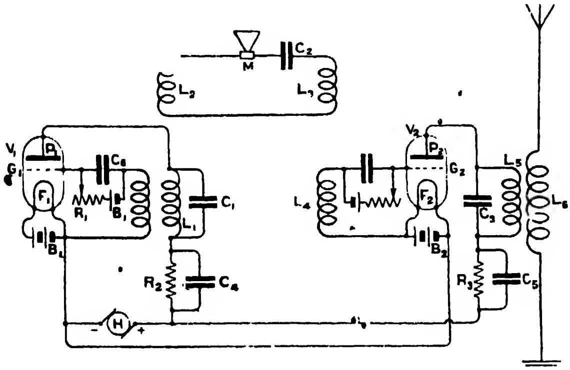


FIG. 292.—Round's wireless telephone, 1914.

were not hard, more regular. Grid circuit resistances associated with batteries were also employed.

The microphone, it is to be noticed, does not handle the whole of the aerial current but only the oscillatory current produced by the left-hand valve, which is sometimes called the *master oscillator*. This is important because microphones are not suitable for carrying heavy currents. The microphone modulates the high-frequency current before it is amplified by the other tube.

Grid Potential Modulation.—Fig. 293 shows an oscillating circuit in which the modulator consists of a microphone connected indirectly in the grid circuit. A step-up transformer T_1T_2 is connected as shown. In the primary circuit is included a microphone M and a small battery B_2.*

* 4 or 6 volts is suitable for microphone use.

When M is spoken into, magnified current variations are induced into the winding T_2 and the potentials are impressed on the grid G of the vacuum tube. The varying potentials on the grid modulate the high-frequency oscillations produced by the valve. It has been previously pointed out that the oscillatory energy of a generating valve depends on its grid potential. The best results are obtained when the grid base-line or normal operating potential is half-way along the grid-potential—anode-current curve. If the grid base-line potential be increased so that the normal operating point is moved towards saturation the output of the valve will gradually fall until the valve suddenly stops oscillating. Likewise, the amplitude of the oscillations decreases as the grid potential becomes more negative. In the Fig. 291 circuit, the microphonic potentials vary the grid base-line potential and thus the output of the valve. The system is not very good and its action is critical. The valve is liable to stop oscillating. The blocking condenser C_2 acts as a by-path for the H.F. current. The modulated oscillations are induced into the aerial circuit. The anode circuit could, if desired, form part of the aerial circuit.

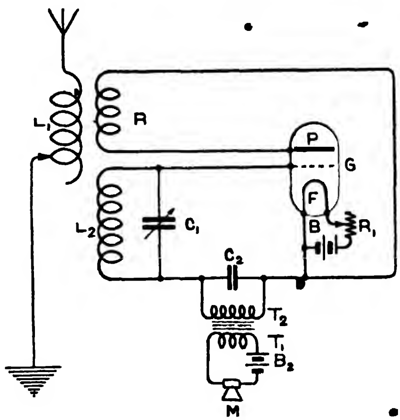


FIG. 293.—Wireless telephone employing grid potential modulation.

The circuit may be modified in many ways. The winding T_2 might be connected across the condenser C_1. Other modifications are possible and may be arranged by applying this method of modulation to the C.W. transmitters of Chapter XI.

Western Electric Company - Colpitts System. — The Western Electric Company and E. H. Colpitts have developed several wireless telephone circuits. A 1914 type is shown in Fig. 294. The anode oscillatory circuit consists of the anode, C_2, L_3, L_2 connected across an impedance Z, which allows the passage of the D.C. anode current but not the H.F. oscillations.

This form of separating the H.F. and D.C. components of the anode current is already familiar to the reader. The grid oscillatory circuit L_4C_3 is similarly connected across an impedance T_2 which is also the output winding of a simple modulator circuit. The coil L_3 is coupled to L_4 and the whole system oscillates of its own accord, the oscillations being passed on to the aerial circuit through the coupling between L_2 and L_1. By speaking into the microphone M potential variations appear at the ends of T_2 and are impressed on the grid of the vacuum tube, thereby modifying the oscillations. The circuit, however, acts, no doubt, in another way. The low-frequency microphonic potentials impressed on G produce magnified surges in Z which increase or decrease the anode voltage on P. Since the output of an oscillating tube is directly propor-

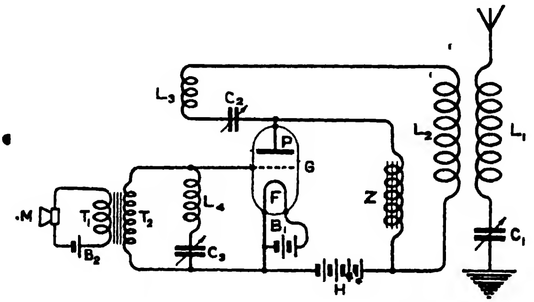


FIG. 294. – Western Electric Company-Colpitts system.

tional to the anode voltage, it is easy to understand that the modulation may be attributed to this effect. This circuit is described in British Patent 141047 (May 18/14), applied for by Western Electric Co.

This general class of circuit has not proved altogether satisfactory as the variations of grid potential due to the microphone are liable to stop the circuits oscillating.

Latour's Wireless Telephone Circuits.—A circuit is described by Marius Latour in British Patent 132118 (Nov. 30/16). This arrangement in one form appears similar to Fig. 294. In another the impedance or choke Z is in series with the D.C. anode circuit. The microphone transformer is also in series with the grid oscillator circuit.

De Forest Radio Telephone.—Fig. 295 shows a very simple wireless telephone designed by Lee de Forest and described in British Patent 101415 (Sept. 4/15). The

circuit shown has been redrawn from the specification to demonstrate its action more clearly. As usual in de Forest circuits, the oscillatory circuit L_2C_1 is connected across grid and plate of an "oscillion" or transmitting tube. A stopping condenser C_2 prevents the grid being affected by the voltage supplied by dynamo H. An impedance Z is included in the anode circuit as usual. A resistance R is connected between grid and filament and has a value of from 25 to 100 ohms. This acts as a leakage path and its conductivity determines to a large degree the energy of the oscillations set up by the "oscillion." For example, while the high-frequency current induced in the aerial circuit may be of, say, two or three amperes, the leakage current through the resistance R will be only a few milliamperes. Consequently a voice controlled device, such as a microphone, may be inserted in such a leakage path and carry only small currents yet by suitable changes in its resistance produce proportional changes, but of many times the intensity, in the high-frequency current in the aerial circuit.

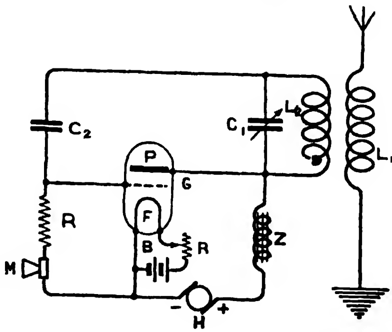


FIG. 295.—A de Forest wireless telephone circuit.

In Fig. 2 of the above specification, a modification is shown in which the secondary coil of a telephone transformer is placed across the resistance R.

A valve may be connected in series with the grid of a wireless telephone transmitter. The valve is so connected that an electron current would flow from the grid of the oscillating valve to the filament of the modulator valve, thence to the plate of the modulator and so to the filament of the generating tube. The microphone transformer secondary is connected across grid and filament of the modulator tube. Circuits on these lines are described in Beauvais' British Patent 131018 (Dec. 14/17).

In British Patent 107001 (May 23 16), L. de Forest and C. V. Logwood describe systems for wireless telephony. One of the circuits given is reproduced in Fig. 296. The microphone

is represented by M. The inventor states that it is an advantage to connect the condenser C_4, or an inductance shown in dotted lines at L_2, across the microphone M, as clearer articulation is obtained at the receiving station.

General Electric Company Circuits.—In British Patent 11708/14 (Oct. 16/13). Schiessler suggested the use of a two-electrode tube containing rarified gas as a leakage path across the aerial inductance or other suitable power circuit. The energy deflected through this valve was to be controlled by an external magnetic field operated by a microphone. By diverting energy from the aerial, modulation could be effected. The use of a three-electrode valve for a like purpose has been suggested by the G.E.C. (U.S.A.). Fig. 297 shows a circuit by the G.E.C. (U.S.A.) and August

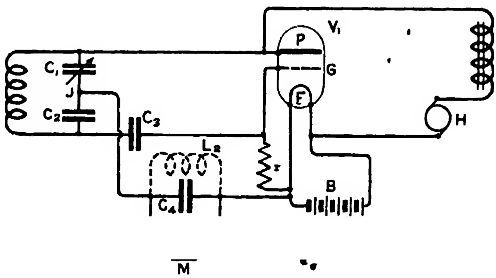


FIG. 296.—Another de Forest wireless telephone circuit.

Hund described in British Patent 21388/14 (Oct. 22 14). A generator A of continuous oscillations sets up the oscillations in the aerial circuit. The generator may consist of an arc, high-frequency machine, or vacuum tube generator. It will be understood that any of these generators may be used whenever a H.F. generator is shown in a diagram. A vacuum tube V has two separate plates P_1 and P_2, grids G_1 and G_2, and a filament F. A large part L_1 of the aerial inductance is connected across the two plates P_1 and P_2. The middle point J of the inductance L_1 is connected to the filament F. A secondary winding of a microphone transformer T_1T_2 and a potentiometer arrangement BR_3 are connected across the filament F and the grids, which are connected together. Now, when oscillations are taking place in the aerial, the two ends of L_1—and therefore the two plates P_1 and P_2—are of opposite polarity relative to the middle point of L_1, which is connected to the

filament F. Consequently the plates are alternately positive and negative and an electron current would normally flow to the two plates in turn, the leakage thus tending to damp out the aerial current. If, however, we give the grid a negative voltage by means of the potentiometer BR_3 we can prevent the flow of electrons to the anode, or limit it as required. When the microphone M is spoken into, the varying potentials of the grids varies the electron flow from filament to the operative anode, and therefore the amount of leakage of aerial current. The amplitude of the oscillations in the aerial circuit is thus varied. The resistances R_1 and R_2 are included in the anode

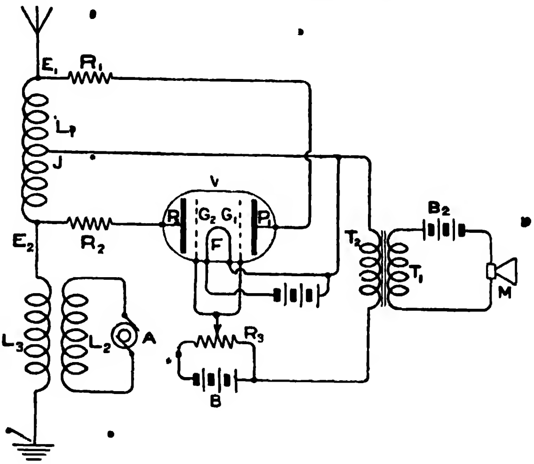


FIG. 297.—Hund's wireless telephone arrangement.

circuits.* It will be seen that the valve V will dissipate a great deal of energy which would have been radiated from the aerial. Energy from the top half of L_1 will be absorbed during one half cycle of aerial current, and energy from the lower half during the other half-cycle.

Thus energy is absorbed during both half-cycles.

Some general remarks on absorption systems may be useful here, although the development has not necessarily been due only to the G.E.C.

Sometimes the absorbing circuit is coupled to the antenna circuit. Energy is in some arrangements continually being dissipated in the anodes of the modulation valve. The

* These improve articulation. The diverted energy is also largely dissipated in R_1 and R_2.

amount dissipated varies with the microphone potentials on the grid or grids. Dissipation systems by absorbing energy from the antenna are very wasteful but good speech is obtained. The wave-length changes slightly while speech is proceeding. This is because the frequency of an oscillatory circuit with a resistance (in this case the absorption valve) across it depends somewhat on the value of that resistance.

In British Patent 7367/15 (May 17/15) the G.E.C. show an absorption scheme in which only one ordinary valve is used.

Fig. 298 shows the generator A of continuous waves included in the aerial circuit. The secondary L_2 of a radio frequency transformer L_1L_2 is connected across the anode P and filament F of a vacuum tube V. The current in the aerial will depend on the current absorbed from the secondary circuit L_2. This latter current depends on the conductivity of the vacuum tube which is made to vary by causing microphonic potentials to influence the grid G. It is to be noted in this particular circuit that the valve is only conductive to those half-oscillations which make the anode P positive. It is these half-cycles which will be modulated.*

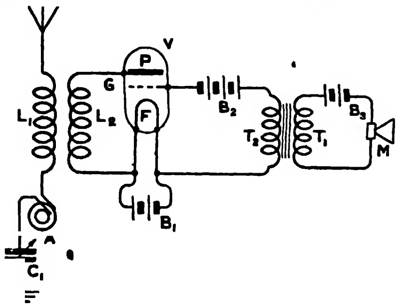


FIG. 298 – Another form of G.E.C. wireless telephone employing a three-electrode valve as an absorbing device across a circuit coupled to the aerial circuit.

Fig. 299 shows an arrangement in which the H.F. generator A is included in an intermediate circuit coupled to the aerial circuit by L_1L_2 and to the variable vacuum tube resistance through L_3L_4 which is preferably so designed as to give a comparatively large secondary voltage. Two vacuum tubes V_1 and V_2 are so arranged that the oscillating current from the secondary L_4 passes alternately through the conducting path from filament to anode of each valve. A microphone M and microphone transformers T_1T_2 and T_3T_4 are so arranged that whichever tube is in use as a shunting resistance the value of its conductivity is varied by means of potentials on

* L. de Forest in British Patent 149272 (May 10/15) describes a similar circuit with a fixed anode voltage.

its grid caused by speaking into M. The current in L_4 will consequently vary and so the energy radiated from the aerial will be modulated. Grid batteries B_3 and B_4 are as usual connected in the grid circuits in order that the most suitable normal potential may be given to the grids.

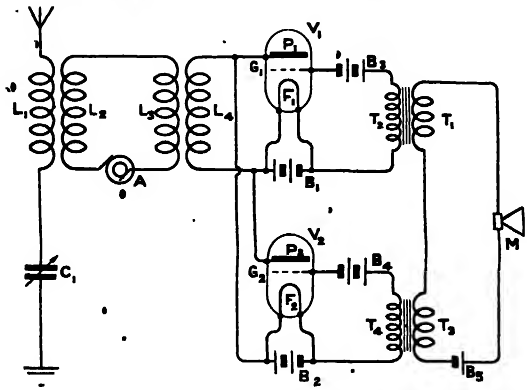


FIG. 299.—Full-wave absorption circuit.

Fig. 300 shows the arrangement of Fig. 299 modified. We are now using a single vacuum tube containing two grids G_1 and G_2, and two anodes P_1 and P_2, and one filament F.* A middle tapping J_1 is taken from the secondary winding L_4 to

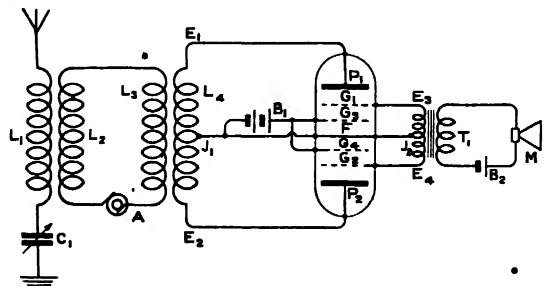


FIG. 300.—A special valve in a circuit used by G E C. (U S.A.) for absorbing both half cycles.

the filament, while the ends are connected to the two plates P_1 and P_2. This arrangement allows the oscillating current to pass through the tube by the two paths alternately. One single microphone transformer M is used, a half-way tapping J_2 on its secondary winding being connected to the filament, the

* No means of heating F is shown.

two ends being joined to the two grids. The action of this circuit is similar to that of the previous one. The circuit may, of course, be modified by amplifying the microphonic currents before impressing their E.M.F.'s on the grids G_1 and G_2. Additional grids G_3 and G_4 are sometimes used, and by giving them a positive potential by means of the battery B_1 the electron current is greatly augmented and makes high plate voltages unnecessary. Negative potentials could be applied if desired.

A G.E.C. Modulator.—Fig. 301 shows another scheme

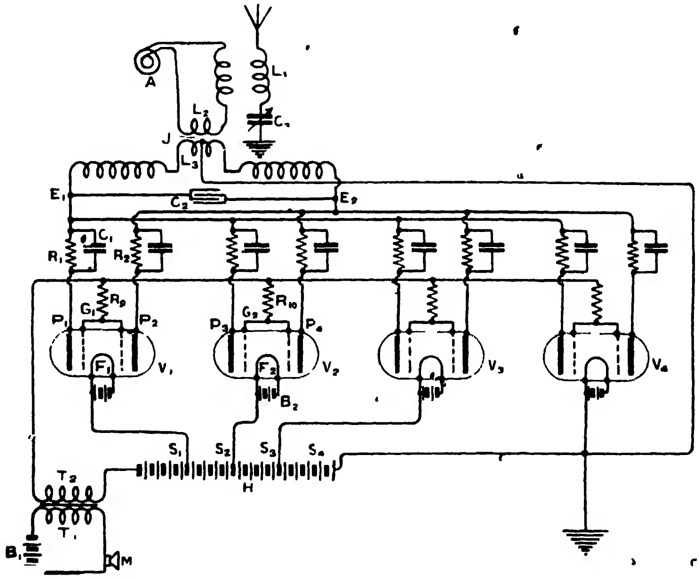


FIG. 301.—A G.E.C. wireless telephone using progressively absorbing vacuum tubes.

devised by the G.E.C. and described by the British Thomson-Houston Company, Ltd. (their agents in Great Britain) in British Patent 102700 (Oct. 19/15). The main carrier wave is supplied by the high-frequency generator A. The modulating device consists of a number of vacuum tubes V_1, V_2, V_3, V_4, which are made to act as conductors and so provide a leakage path for the high-frequency current. Energy from the closed circuit L_3C_2 will be absorbed by the tubes and this withdrawal of energy will modify the current in the aerial.

The conductivity of the tubes V_1, V_2, V_3, V_4 is varied by potentials supplied by a microphone M through a transformer T_1T_2 to the grids G_1, G_2, etc. Normally, we might expect several tubes to be connected in parallel in order to control greater energy, in which case the amount of energy which could be controlled would vary directly with the number of tubes used. The G.E.C., however, present an arrangement in which the amount of energy which can be controlled will vary substantially as the square of the number of vacuum tubes used.

Let it be assumed that the grid G_1 of tube V_1 is given a negative potential by the battery H such that little or no current will flow through the tube when the H.F. potential supplied by circuit L_3C_2 is applied to the anodes P_1, P_2. The negative potential of the grids of the tubes V_1, V_2, V_3, V_4, with respect to their filaments, will be progressively greater. If now a current wave is produced in the transformer T_1T_2, caused by speaking into M, of such a direction as to overcome the negative potential of the grid G_1 of V_1, current will begin to flow first through the tube V_1 and will gradually increase to a maximum value. If the potential of the current wave is great enough, it will gradually overcome the negative potential of all the grids and current will begin to flow successively in the tubes V_2, V_3, and V_4. The tubes may be so designed and the potentials to the grids so chosen that when the current in tube V_1 reaches its maximum, current will begin to flow in the tube V_2, and when the current in V_2 reaches its maximum current will begin to flow in V_3, and so on.

As shown in the figure, resistances R_1, R_2, etc., shunted by condensers C_1, etc., are included in the plate circuits of the vacuum tubes. When current first begins to flow in the vacuum tube circuit the greater part of the drop in potential will occur in the vacuum tube itself and hence the tube will be called upon to absorb most of the energy of the secondary circuit. As the current increases, however, the drop through the resistance R_1 will increase and the proportionate amount of energy absorbed by the tube will decrease. The maximum energy which the tube will be required to absorb will be when the current has reached one-half of its maximum value and the tube is consuming one-half of the voltage. When the current reaches its maximum value in the tube, the amount of energy which the tube will be required to absorb will be practically negligible, the principal drop being in the resistance.

Suppose now it is desired to control a maximum of 160 kilowatts of energy, which is represented by 8 amperes at 20,000 volts. If we use four tubes as indicated in the drawing, each tube will be called upon to take 2 amperes. The maximum amount of energy which any one tube will be called upon to absorb will be 1 ampere at 10,000 volts or 10 kilowatts. The change from minimum to maximum in each tube, however, will occur in one quarter of the time required in the case where a single tube was used. Hence the average amount of energy absorbed will be only one quarter of 10, or 2·5, kilowatts. Thus it will be seen that four tubes of the same capacity will be able to control 16 times as much energy as the single tube.

In the type of tube shown there is an appreciable capacity between the anodes. This results in considerable current flowing through the tube between the anodes when the system is not being used for transmitting signals. As a result a large amount of energy is needlessly wasted in the resistance R_1, R_2, etc. In order to avoid this it may be desirable to shunt each of these resistances by a condenser C_1. This will cut down the H.F. alternating current, but will not interfere with the unidirectional flow of current through the tube between the cathode and anodes. In order to prevent the grids G_1, G_2, etc., from consuming an unnecessary amount of current when they become highly positive, resistances R_1 may be connected in series with them.

Marconi 15-K.W. Wireless Telephone.* —*The Wireless World* has described a 15 K.W. wireless telephone used by Marconi's Wireless Telegraph Company. The diagram of connections is shown in Fig. 301. The source of power is a 200 cycle, 500 volt, 15 K.W. alternator, which feeds a step up transformer. The condenser K_1 is charged to about 10,000 volts by the full-wave rectification obtained with the two valves. The anode oscillatory circuit is coupled to the direct anode circuit by means of a condenser. The grid oscillatory circuit R is aperiodic.

The anode oscillatory circuit is coupled to the separate aerial circuit L_1. It is to be noticed that no ripple eliminator is used. A hum is consequently heard at the receiving station when speech is not being transmitted.

* Lee de Forest has also produced somewhat similar arrangements. See British Patent 149272 (May 10/15).

This principle of absorption has been largely used by the G.E.C. (U.S.A.). The modulating circuits are shown to the left of the figure. A microphone impresses potentials on the grid of an amplifying valve. A second valve amplifies the speech potentials still further, and they are then applied to the grid of a third valve, which acts as a conductor in shunt with the aerial inductance L_1. The amount of energy absorbed by this valve will depend on its conductivity, and this varies according to the potentials applied to its grid. In this manner, speech in the microphone will produce proportional variations in the aerial current. The anode voltage for the amplifying tubes is obtained from the reservoir condenser K_1. All the filaments of the various valves are heated by alternating current.

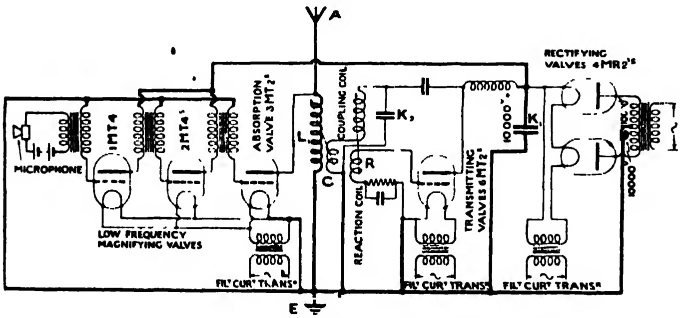


FIG. 302.—A Marconi 15-K.W. wireless telephone transmitting circuit which has been used at Chelmsford.

Although single valves are shown in the figure, yet in practice several valves may be connected in parallel to replace one valve where shown in the circuit. The first amplifying valve consisted of one MT_4 valve; the second stage two MT_4 valves; the third of three MT_2 valves; the oscillators consisted of six MT_2 valves; the rectifiers each consisted of two MR_2 valves.

A fortnight's test with this 15 K.W. set in March, 1920, resulted in a telephonic range of about 1,000 miles, using ordinary wireless telegraphy receivers.

Another Form of Absorption Circuit.—In British Patent 131553 (March 6/19) the G.E.C. show another form of absorption telephone circuit. When unravelled, the arrangement is very similar to Fig. 303. The vacuum tube V_4 and its associated circuits is simply a source of high-frequency continuous

oscillations which are induced into the coil L_2. The impedances Z_3 and Z_4 are radio-frequency chokes. The high-frequency potentials across an adjustable portion of L_2 are communicated through C_2 and the choke Z_5 to the grid G_1 of an amplifying vacuum tube V_1. The grid G_1 is given a suitable negative potential by B_1 through the impedance Z_2. The direct current in the anode circuit of V_1 is supplied by D through the radio-frequency choke Z_1. The amplified H.F. current is developed in the antenna circuit. The oscillatory circuit is thus in parallel with the D.C. circuit. The energy in the aerial circuit will depend on the amplitude of the oscillating potentials applied to the grid G_1 of the power amplifier, These potentials are damped by the valve V_3. A simple amplifier circuit enables the microphone M to vary the conductivity of V_3

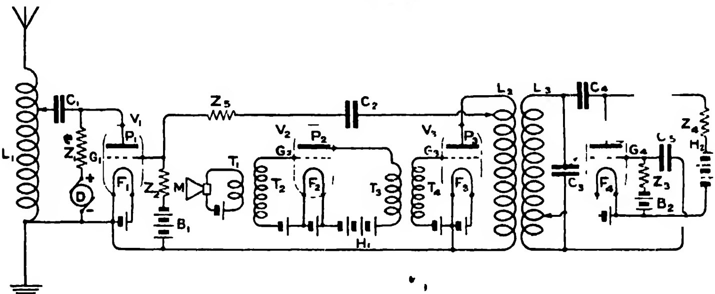


FIG. 303.—A G.E.C. wireless telephone.

by altering its grid potential. In this manner the microphone controls the amount of energy absorbed from the input side of V_1 and thus modulates the H.F. output of V_1.

In British Patent 7367/15 (May 17 15), the General Electric Company describe a circuit which is reproduced in Fig. 304. The vacuum tube V_1 acts as a generator in the ordinary way. Retroaction between L_2 and L_3 sets up continuous oscillations in L_2 which are transferred to the aerial circuit L_1. The battery B_1 is for varying the normal potential of the grid G_1. Normally there is not a large grid current and there is little damping of the oscillations in L_3C_1 due to such a current. If, however, we were to connect a resistance across the grid oscillatory circuit the damping of the oscillations would be great and the amplitude of the waves emitted would be decreased. The three-electrode tube V_2 of Fig. 304 acts as the resistance, and the value of this resistance is varied by

speaking into the microphone M. A plain resistance is not used but the conducting path between the filament F_2 and the anode P_2. Now the resistance of the conductive path between F_2 and P_2 may be varied by altering the potential of the grid G_2. When this grid is sufficiently negative, no electrons can pass to the anode, and the resistance across the grid oscillatory circuit of the first tube is infinite and no damping occurs. If, however, the grid G_2 has a potential sufficient to allow an electron current to flow, the shunt resistance path across the grid oscillatory circuit will have a value depending on the potential of G_2. Consequently variations of the potential of G_2 produced by the microphone transformer T_1T_2 will

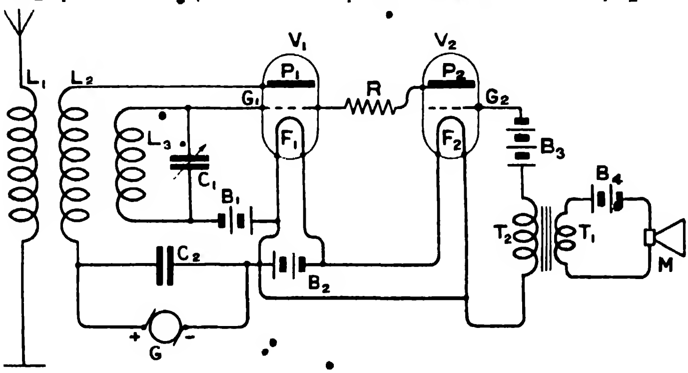


FIG. 304.—A General Electric Company (U.S.A.) circuit employing an absorption three-electrode tube.

vary the damping of the oscillations in L_3C_1 and so vary the amplitude of the emitted waves.

It is to be noted that the frequency of the oscillations in the grid oscillatory circuit depends to a certain extent on the resistance across it. Since this resistance is continually varying when speech is being transmitted, the wave-length of the waves emitted will also vary and is liable to impair the purity of the speech received. In order to prevent this, it may be found desirable to employ a resistance R in the position shown. This resistance also lessens distortion and a portion of the diverted energy through V_2 is dissipated in R.

Other Absorption Circuits.—In British Patent 144803, the G.E.C. (U.S.A.) describe another full-wave absorption scheme which resembles closely the arrangement of Fig. 297.

In British Patent 15448 (Nov. 2 15), the G.E.C. show

interesting circuits in which the filaments are heated by alternating currents,' the connections to the filaments being made at the middle point of the secondary windings of the transformers which supply current to heat the filaments. One of the circuits (Fig. 305) shows the use of an absorbing

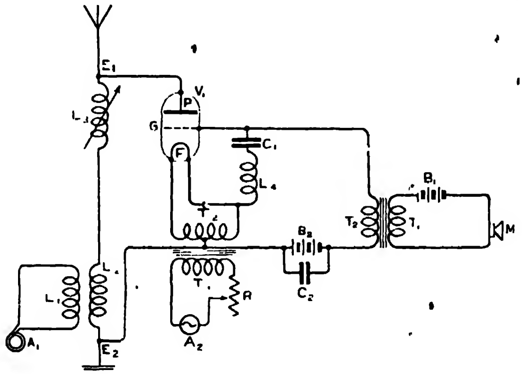


FIG. 305.—An absorption circuit with an oscillation circuit across grid and filament.

three-electrode tube. Across grid and filament is a condenser C_1 and inductance L_4 in series. These are to prevent the fluctuating high anode potentials having an electrostatic effect on the grid potentials.

Valve Conductor Systems.—A modulation system which gives suitable results consists in utilising a three-electrode valve as a conductor through which high-frequency currents pass and excite an aerial circuit. The current passed by the valve is varied by microphonic potentials on the grid. One form of such circuit (taken from British Patent 14769/15 (Oct. 19, 15) is shown in Fig. 306. The energy in L_2 depends on the degree to which the valve V will conduct the current supplied by the H.F. generator A. This conductivity depends on the potential of G. In this

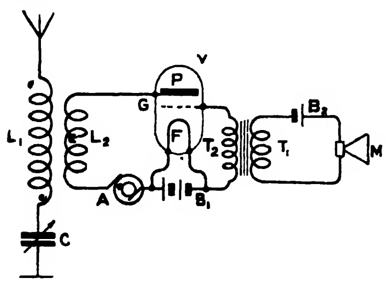


FIG. 306.—A three-electrode tube used as a variable conductor in radio-telephony.

manner the microphone is capable of modulating the output from the aerial. It would appear that the losses in V (which is usually of high resistance) would minimise the value of this arrangement. Others have suggested the use of two valves to conduct both half-cycles of high-frequency current.

A Western Electric System of Modulation.—A novel system of modulation devised by the Western Electric Company (U.S.A.) consists in applying modulated *high-frequency* potentials to the grid of an impedance valve connected in the C.W. generator circuit.

Fig. 307 may help to explain the arrangement. A high-frequency generator A_1 supplies current to the primary L_2 through two valve impedances V_1 and V_2 which are connected in a reverse manner so that both half-cycles pass through one or other of the tubes.

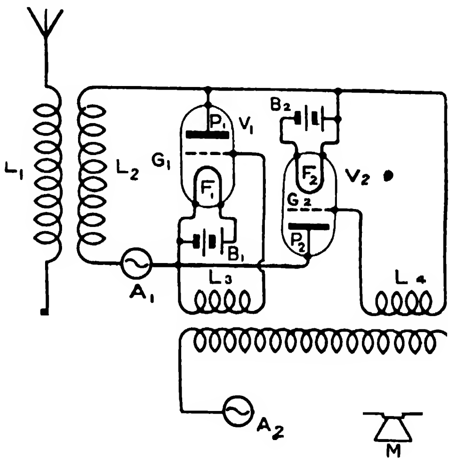


FIG. 307.—To demonstrate the principle of a method of modulation devised by the Western Electric Company (U.S.A.).

The power radiated will depend on the conductivity of the valves V_1 and V_2, and this conductivity may be varied by applying potentials to the grids G_1 and G_2. The potentials applied to G_1 and G_2 might be the ordinary low-frequency potentials supplied by a microphonic transformer, but in this system of modulation, the Western Electric Company prefer to apply high-frequency oscillating potentials to the grids. The phase and frequency of the potentials on the grids is made to coincide with the frequency of the oscillations supplied by A_1. The resultant current through L_2 will still be of sine form, but if the potentials applied to G_1 and G_2 be modulated, as, for example, by a microphone, the current in L_2 will be also duly modulated. In Fig. 307 the inductances L_3 and L_4 transfer the modulated potentials of L_5

to the grids G_1 and G_2. The source A_2 supplies high-frequency current having a frequency equal to that supplied by A_1. This current is modulated by M. The inductances L_3 and L_4 are so coupled that no matter which valve is operating, its resistance will be varied in accordance with the modulations produced by M. It is obvious that the same generator A_1 could replace A_2.

In Fig. 308 we see Fig. 1 of British Patent 132058 (Sept. 14 '18), which describes the complete system of modulation in its practical form. One main generator A is employed. The windings L_6 and L_7 correspond to the inductances L_3 and L_4 and both receive energy induced by the inductance L_5, which is included in a microphone circuit L_5, C_2, portion of R, L_4, M, the microphone being represented by M. The microphone circuit receives the high-frequency current to be modulated from a circuit L_3R, connected across the generator A. The relatively adjustable coils L_3 and L_4 and the adjustable resistance R varied by adjusting S_2) comprise a phase-adjusting device whereby the voltage applied to the grids G_1 and G_2 may be given a proper phase with respect to the generator voltage applied to the anodes of the tubes V_1 and V_2. A relatively small amount of high-frequency energy is transferred by means of the coils L_3 and L_4 into the circuit containing L_5, which may be tuned to the

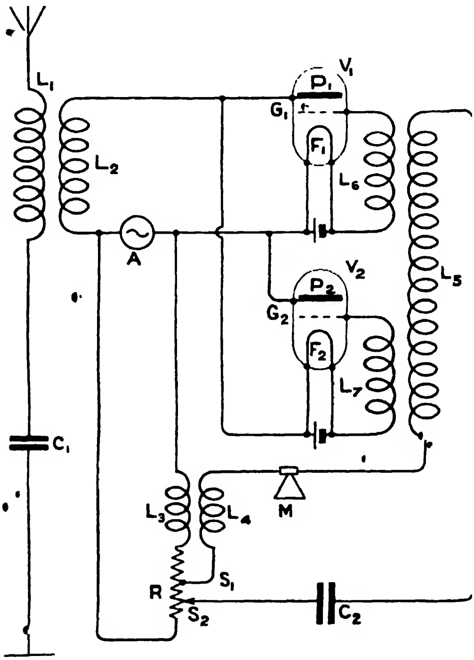


FIG. 308.—Western Electric system using modulated H.F. potential on grids.

frequency of the generator. Under these conditions the current flowing in the circuit containing L_5 will depend solely upon the resistance and will be very sensitive to any variation in the resistance of the microphone M. It is to be noted that the microphone M might be replaced by a condenser transmitter (*i.e.* a condenser microphone) whose capacity would be varied by the voice. The microphone circuit would thus be thrown out of tune and a modulation effect would be obtained.

In Fig. 2 of the patent specification, the inductance L_3 and resistance R are shown in series with another inductance coupled to the coil L_2. In the third figure, the tubes V_1 and V_2 are shown in parallel with the coil L_2 and the generator A, the inductance L_3 and resistance R being connected across A. Although only two impedance tubes are described, yet each might be replaced by several in parallel if desired. The grids may be given a suitable negative potential by means of batteries.

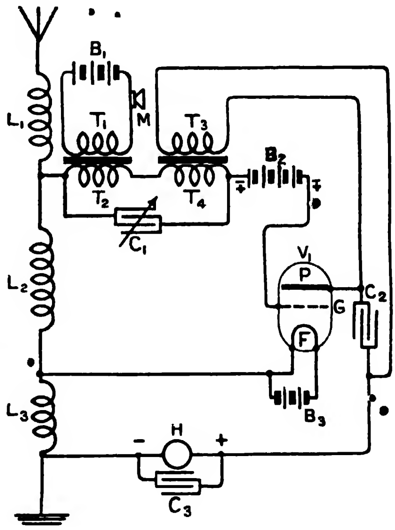


FIG. 309.—G.E.C. wireless telephone using low-frequency retroaction.

Wireless Telephone using Low-frequency Retroaction. In British Patent 127325 (April 1917), the B.T.-H. Company (for the G.E.C. of U.S.A.) describe a wireless telephone circuit shown in Fig. 309. Vacuum tube acts as a generator of continuous waves. The D.C. generator H supplies the anode voltage. This method of producing oscillations in this circuit is similar to that of Fig. 250. A single circuit is employed. The wave-length emitted may be varied by adjusting the aerial inductance L_1.

The microphone is coupled by means of the transformer T_1T_2 to the grid circuit of this oscillating system. The audio frequency variations are amplified by the vacuum tube and

reappear in the winding T_3 which is in the anode circuit. They are induced by T_3T_4 once more into the grid circuit, and thus a retroactive amplification effect is produced. Condensers C_1C_2 and C_3 by-pass H.F. currents.

The second figure of the patent shows a similar arrangement in which the H.F. and L.F. circuits are in parallel, stopping condensers being used in the usual way.

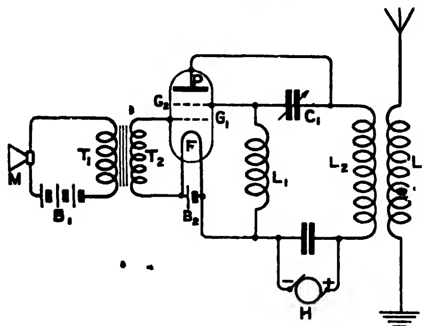
In connection with this patent reference has been directed to specification No. 107001 (Lee de Forest's wireless telephone and oscillation generator).

Use of Four-electrode Vacuum Tube.—In the simple wireless telephone circuit of Fig. 293 the microphonic currents are superimposed on the oscillating potentials in the grid circuit. This method of control has not been found very satisfactory because of the fact that when the potentials on the grid produced by the microphone are large enough to control efficiently the amplitude of the radiated waves the system becomes unstable and stops oscillating. The best modulation would be obtained if the amplitude of the continuous oscillations were varied between the maximum value and zero. This, however, is not easily done. In the first place, the vacuum tube is liable to stop oscillating. Secondly, it is not usually convenient to obtain from the microphone potentials as great as those which are induced into the grid circuit during the retroactive self-oscillation process.

The General Electric Company, in British Patent 110924 (Nov. 2/16), describe how they overcome these difficulties. To the ordinary three-electrode vacuum tube is added a second grid so arranged and designed that the control exercised by it is equal to that of the ordinary grid but is accomplished with smaller potentials. For example, the grid might be closer to the filament, in which case the small microphonic potentials would have the same effect on the anode current as the larger oscillating potentials on the ordinary grid situated further from the filament.

Fig. 310 shows a circuit connected up for wireless telephony. The grid oscillatory circuit consists of the inductance L_1 which forms part of a single oscillatory circuit $L_1C_1L_2$. A source H of high voltage is connected in the anode circuit in the usual way. The anode oscillatory circuit is coupled to the aerial inductance L_3. The novel feature is the connecting of

the secondary T_2 of the microphone transformer T_1T_2 across the additional grid G_1 and the filament F. As long as there is no variation of the current flowing in the local circuit of the microphone M the potential of the grid G_1 will be constant and this grid will play no part in the operation of the circuits. Under these conditions, high-frequency oscillations will be set up in the aerial in the well-known manner. As soon, however, as the current in the local circuit of the microphone M varies, the potential of the grid G_1 will vary, and there will be a corresponding variation of the current flowing in the anode circuit of the vacuum tube. By this means, while a variation of several hundred volts upon the grid G_2 may be desirable to secure a maximum output of H.F. current, a much smaller potential variation upon the grid G_1 may be sufficient to vary the current flowing in the anode circuit between a maximum and zero.



310.—Use of two grids in an oscillating vacuum tube.

Van der Bijl's modulating Circuits.—H. J. Van der Bijl has devised a class of circuits suitable for modulating high frequency currents at speech frequency. One of these circuits is shown in Fig. 311. An impedance path Z, which also forms the output circuit of a vacuum tube, is connected in series with the aerial, which is energised by the high-frequency generator A. Speaking into the microphone M varies the

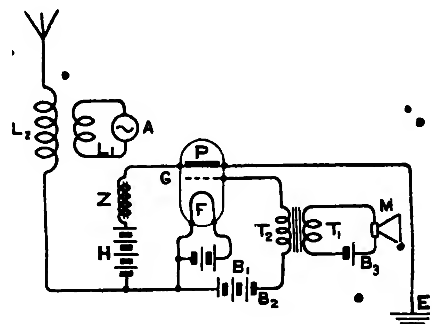


FIG. 311.—Van der Bijl's method of modulation by varying an impedance in series with the aerial.

impedance of Z and so varies the high-frequency radiation from the aerial.

Fig. 312 shows a modification. The impedance Z is

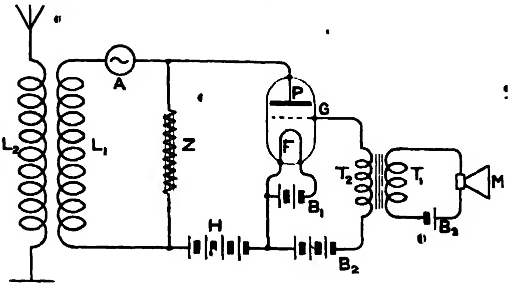


FIG. 312.—Another form of Van der Bijl's wireless telephone.

now connected as shown, the effect, however, being similar to that obtained when Z is in series with the aerial.

Circuit of the Société Française Radio-Electrique.—Fig. 313 shows a microphonic arrangement suggested by the Société Française Radio-Electrique in British Patent 127008 (Feb. 15 16). The ordinary generator of continuous waves is used. The grid oscillatory circuit L_2 is coupled to the anode oscillatory circuit L_1, which forms part of the aerial circuit. A source H of anode E.M.F. is connected as shown. The negative end of the filament is connected to earth.

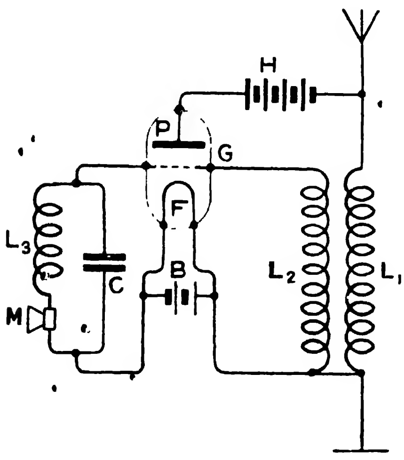


FIG. 313.—Circuit of the Société Française Radio-Electrique.

The distinctive feature consists of an impedance, made up of an inductance L_3 and a capacity C (branched in parallel and sensitively tuned to the frequency of the oscillations produced) connected across grid and filament. This impedance can easily be made very great and of the order

of magnitude of the vacuum tube resistance between filament and grid. The microphone M is placed, for instance, in series with the inductance. Under these conditions the impedance is proportional to the resistance of the microphone and the variations of resistance of the microphone produce corresponding variations of the impedance. It is stated that the results are the same as if a microphone of very great resistance had been shunted across the grid and filament. Such an arrangement is preferable to using a microphone of ordinary resistance. The microphone might if desired be placed in series with the capacity C to obtain the same results. A second figure

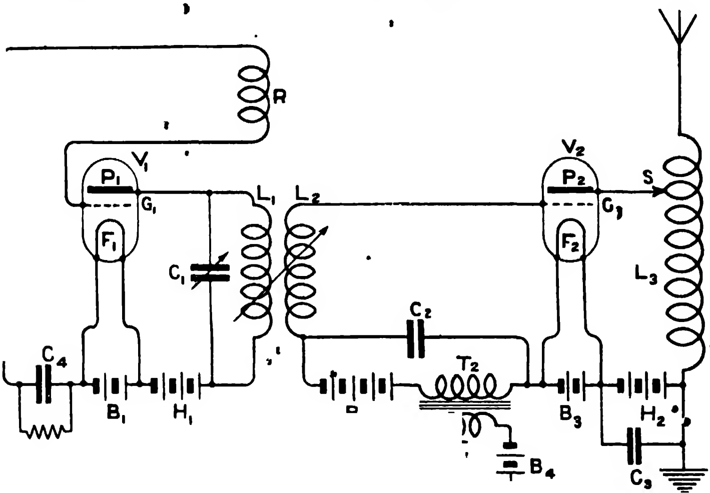


FIG. 314.—A radio telephone system with separately excited grid circuit.

shows the device in use on a C.W. generator in which a three-phase alternator is employed to supply the E.M.F. of the anodes. Three vacuum tubes are used.

Separately Excited Grid Systems.*—The wireless telephone of Fig. 314 shows the use of an amplifying valve whose output circuit is coupled to an aerial system. A local oscillator (such as a valve) induces continuous E.M.F.'s into the input or grid circuit of the amplifying valve, the normal grid potential of which is varied by the potentials from a microphone transformer. The essential circuit is shown in Fig. 314. The source

* See also Western Electric Co.'s British Patent 141732 (Aug. 21/15).

V_1 of local oscillations induces continuous oscillations into the grid circuit of the amplifier tube V_2. The grid G_2 of this tube is given a high negative potential which brings the operating point or grid base-line well to the left of the bottom extremity (representing zero current) of the grid-potential—anode-current curve of the amplifier tube. The oscillating potentials on the grid G produce no output in the anode circuit of V for this reason. When, however, the microphone M is spoken into, the grid base-line, during the positive half-cycles of microphone potential, becomes less negative and the output from the valve V_2 will depend on the degree to which the anode current curve is utilised; in other words, on the amplitude of the microphone potentials. It will be appreciated that no energy is radiated except when speaking—a desirable feature.

Means of Obtaining Negative Grid Potential.—In practice, the negative potential for the grid of the amplifier tube may be obtained by connecting a leaky grid condenser in the filament side of the grid oscillatory circuit of the oscillator. This leak is preferably of the order of 80,000 ohms and is best wound with wire. It is also convenient to have tappings from this leak so that any desired voltage may be used for special purposes such as for giving the grid of the amplifier tube a negative potential. When oscillating potentials are taking place across the grid circuit of an oscillating vacuum tube, the grid becomes positive during the positive half-cycles and the resultant current in the grid circuit is considerable, and of the order of several milliamperes in small wireless telephone transmitters. The grid leak must therefore be capable of carrying this current. The flow of current through the grid resistance gives the grid of the oscillating tube a suitable negative operating potential. To find this potential in an actual circuit it is only necessary to measure the current and multiply it by the value of the resistance.

It is also frequently very convenient when the former valve is acting as a generator and not as an amplifier to use the potential across its grid resistance to give the modulator valve a suitable grid potential. These arrangements are described in British Patent 146519 (Oct. 2/16) of Western Electric Co.*

Another Circuit with Separate Grid Excitation.—In British Patent 146610 (April 10/19), P. P. Eckersley describes a wireless

* See also N. Lea's Patent 130520 (Nov. 4/18), and G.E.C. (U.S.A.) Patent 148128 (Jan. 3/19).

telephone arrangement in which a valve supplies high-frequency potentials to the grid circuit of an amplifier tube whose output circuit is coupled to the aerial. The source of E.M.F. for the anode circuit of the amplifier tube is supplied by the microphone transformer. The output of an amplifying tube is directly proportionate to the anode potential, and so good modulated speech is to be expected from this arrangement. Since the energy from a microphone transformer is only about six watts at the most, valve amplifiers may be used to supply the necessary power. It is to be noted that no radiation takes place except during speech transmission. It is, however, possible to have a permanent source of E.M.F. in the anode circuit of the H.F. amplifying tube. The patentee has stated that the results obtained from this arrangement are not very good.

L. B. Turner's and R. H. Wagner's Wireless Telephone.—In British Patent 137098 (Dec. 24 18) L. B. Turner

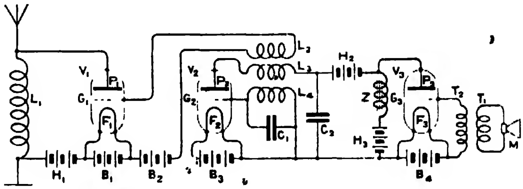


FIG. 315.—Turner and Wagner's wireless telephone.

and R. H. Wagner describe a wireless telephone arrangement which is illustrated in Fig. 315. It is well known that in the usual modulation arrangements, the modulator circuits absorb as much power as the oscillating valve. The modulator valve is also usually of the same size as the oscillator tube. The present circuit does not involve high-powered control circuits.

A small oscillator valve V_2 produces the original high-frequency current through the retroaction between the coils L_3 and L_4. The amplitude of this high-frequency current is modulated by the usual choke-coil method, an impedance Z being included in the anode circuit of the amplifying valve V_3. The anode potential of V_3 is less than that in the case of the tube V_2, and so the anode battery is divided into two portions H_2 and H_3. A by-path condenser is connected from the positive

side of H_2 to the filament of V_2. The modulated high-frequency current in L_3 is passed on to an inductance L_4 and applied to the grid of a high-power valve V_1, which acts as an amplifier of the oscillations. The grid of V_1 is kept at a suitable negative potential by means of the battery B_2. The power for the anode circuit of V_1 is provided by the source of E.M.F. H_1. It is interesting to note that these amplifying arrangements result in a radiation whose wave-length is almost independent of the dimensions of the antenna circuit. In the second figure of the patent a simpler circuit is shown in which the modulation amplifier is omitted. The arrangement lends itself to wireless transmission in which the aerial only radiates when speech waves impinge on the microphone. For example, the oscillating potentials applied to the grid of the main amplifying valve may be made extremely feeble or eliminated altogether except when the conditions governing the oscillations in the master oscillator are modified by the action of speech on the microphone. For example, the anode battery of the oscillator might be adjusted so that the oscillator valve just fails to oscillate. The oscillator will only oscillate when the anode potential is raised by the fluctuation of the microphone current.

A Western Electric Company Wireless Telephone Circuit.—In British Patent 133366 (June 28 13), the Western Electric Co. (U.S.A.) describe a form of choke control, the potentials across the choke varying the potential of the anode of a generating tube.

Another G.E.C. (U.S.A.) Circuit.—In British Patent 139640 the General Electric Company describe a C.W. generator circuit which the present author has described in connection with Fig. 280. This circuit is simply a single-circuit arrangement materially unaffected by the aerial constants. In the second figure of the specification, a wireless telephone circuit is given. A microphone transformer has its secondary included in the grid circuit of the oscillating vacuum tube. In the anode circuit is a radio-frequency choke and also an audio-frequency choke with an iron core. The changes in grid potential cause exactly similar and much greater reactance voltages to be produced across the audio-frequency choke coil. The anode voltage is consequently varied as these reactance voltages add to or are subtracted from the direct current voltage of the generator. The radio-

frequency energy output is directly proportional to the energy input into the anode circuit of the device and the anode energy input is almost directly proportional to the anode voltage. It is therefore clear that accurate reproduction of speech is possible with this arrangement.

Anode Potential Control Circuits.—It has been shown that the power developed in the output circuit of an oscillating vacuum tube is directly proportional to the anode voltage of the tube. By causing microphonic potentials to vary this anode potential, a modulation system is produced. Advantage has been taken of this fact in many modulation systems, and in British Patent 15237 (Oct. 28/15), the B.T.-H. Company illustrate schemes originating from the G.E.C. (U.S.A.) in which a microphone transformer is used to vary the anode potential. The secondary of the transformer is included in the anode circuit and the microphone is connected in the primary circuit. When speaking, the microphone potentials add or subtract themselves from the existing steady potential on the anode. In this a modulated high frequency output is obtained. If the anode battery or other source of E.M.F. is omitted the microphone potentials will serve, but in this case amplifying tubes are used to increase the available energy. When this arrangement is used the valve only oscillates when speaking and poor results are obtained. It is preferable to have sufficient steady E.M.F. in the anode circuit to enable the valve to oscillate feebly. The microphone potentials are frequently amplified by one or more valves before impressing them on the anode of the generating tube. Instead of a transformer a choke coil is very frequently used.

British Air Force Radio Telephone.—The British Air Force radio telephone used during recent years has employed a choke coil instead of a transformer to influence the anode potential of the oscillating valve. The same source of E.M.F. used for the oscillating vacuum tube is also employed to feed the anode circuit of the modulator valve. A 600 volt propeller-driven generator supplied the anode current, and a separate commutator gave about 6 volts which fed the filaments. The development of the British Air Force wireless telephone is described in a paper by C. E. Prince read before the Institution of Electrical Engineers.* Many interesting facts are disclosed and readers may consult the published paper for fuller details.

* See *Journal of the Institution of Electrical Engineers*, vol. **58**, 291.

When speaking into the microphone of this class of wireless telephone, the potentials produced across the choke coil Z vary the anode potential of the oscillating valve between almost zero and twice its normal value.

The receiver consisted of one valve acting as a detector and employing retroaction, followed by two low-frequency valves. More recent receivers employ two stages of high-frequency amplification, one detector, and two stages of low-frequency amplification.

Marconi ½-K.W. Wireless Telephone.—Marconi's Wireless Telegraph Company have produced a ½-K.W. wireless telegraph and telephone set whose connections are illustrated in

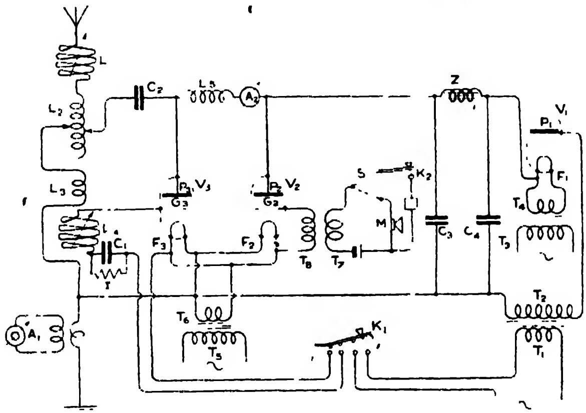


FIG. 316.—A Marconi ½-K.W. wireless telephone.

Fig. 316. The circuit as used for continuous wave transmission has already been fully described in connection with Fig. 283. For wireless telephony a control vacuum tube V_2 is connected as shown. When the switch S is in the lower position, the microphone M and the step-up microphone transformer T_7T_8 impress the voice potentials on the grid G_2 of the control valve. These potentials will produce varying potential surges across the choke Z and so will vary the potential applied to the anode P_3 of the oscillating valve V_3. The key K_1 is kept depressed during speech transmission. When it is desired to transmit by tonic train, or interrupted C.W., the key K_1 is kept depressed and the radiated waves are modulated by means of the signalling key K_2, the switch S being placed in the upper position. The minimum daylight

range for telephony is 100 nautical miles, using an aerial 100 feet high and 220 feet long, the receiver consisting of a Marconi 7-valve amplifier-detector. The tonic train range is 130 nautical miles. The control valve is equal in size to the main power valve. Changing-over from transmitting to receiving is effected by means of a multiple-contact switch.

American Naval Aircraft Wireless Telephones.—The following information relating to American naval aircraft sets has been largely obtained from a paper on the subject by T. Johnson, Jun., read before the Institute of Radio Engineers (vol. 8, 1, Feb. 1920, and vol. 8, 2, April, 1920).

Fig. 317 shows the schematic arrangement of an early

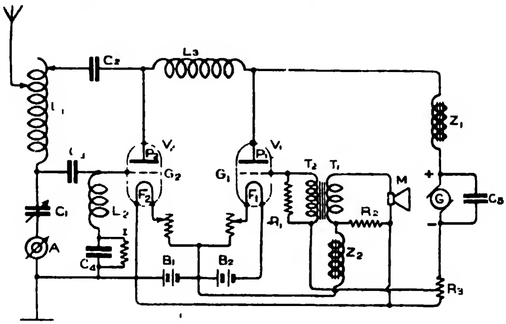


FIG. 317.—A Western Electric radio telephone for naval aircraft

wireless telephone set designed by the Western Electric Company (U.S.A.) for use on naval aircraft. The vacuum tube V_2 is the power oscillator. The direct current anode circuit is P_2, L_3 (an air choke), Z_1 (an impedance), G (a propeller-driven D.C. generator whose voltage is kept fairly steady by the large condenser C_5), a resistance R_3, and one side of the battery B_1 which supplies current to F_2. The aerial oscillatory circuit, which includes the anode oscillatory circuit, is coupled to the direct current circuit of V_2 by means of C_2. The grid G_2 (a coil L_2 and grid leaky condenser C_4 being arranged as shown) is connected through C_3 to a point on the anode oscillatory circuit coupled by C_3 to the anode oscillatory circuit. The potential applied to P_2 is varied by means of the modulator tube V_1, whose anode circuit is in common with the anode circuit of V_2. The voice potentials are applied to the grid of the modulator tube in a somewhat elaborate

manner. The grid G_1 is given a suitable negative potential by taking a tapping from a resistance R_3 included in the anode circuit. The microphone and primary T_1 are supplied with current from the filament accumulator B_1. Resistances R_1 and R_2 were found to improve results. This set possessed telephone range of only 10 nautical miles (18·5 kilometres), the reason being due to faulty modulation. Owing to the excessive size and weight of the set this fault was not remedied. Eight 5-watt vacuum tubes were used in parallel as oscillators.

The General Electric Company (U.S.A.) developed some of the most successful types of wireless telephone. Most of these sets have been of the general type illustrated in Fig. 318. The tube V_2 is the power valve and V_1 the modulator. An impedance Z is common to both anode circuits, which are fed by a generator H or other source of E.M.F. The microphone circuit is connected across grid and filament of the modulator tube. By taking a connection from the leaky grid condenser C_1, the grid G_1 is given a suitable negative value. Ordinary C.W. transmission is effected by including a key K_1 in series with the grid leak *r*. When the key is released, the grid G_2 becomes highly negative and the system stops oscillating. On depressing K_1,* the grid potential returns to its normal value and the system recommences to oscillate. The same effect might be obtained by connecting a separate condenser in series with the leaky grid condenser, and shunting the key across this second capacity. When telephone or tonic train transmission is in progress the key K_1 is kept shorted. If the switch S is over to the right the microphone M is brought into operation. If S is over to the left the buzzer B modulates the continuous waves and tonic train signalling is effected by means of the key K_2. The test

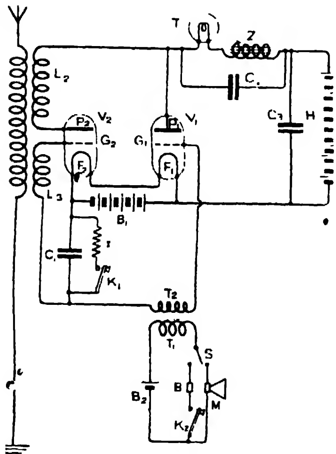


FIG. 318.—Typical G.E.C. circuit used on naval aircraft.

* This key is kept permanently closed for all but C.W. transmission.

lamp T indicates that the modulator tube is functioning correctly. The brilliancy of the filament of T should fluctuate.

A combined low-power wireless telephone transmitter and receiver designed by the G.E.C. (U.S.A.) is shown in Fig. 319. This set (type SE 1345) was designed for lightness and simplicity of control. The power is only 5 watts but the telephone range is as much as 55 kilometres. The switch S_1 changes the aerial from "send" (left side) to "receive." The aerial circuits are tuned by means of variometers. The receiving circuit consists of a detector followed by two audio-frequency amplifiers. The first vacuum tube works with 20 volts from H on the anode and the amplifying tubes take 40 volts. By means of the switches S_2 and S_3, the battery H

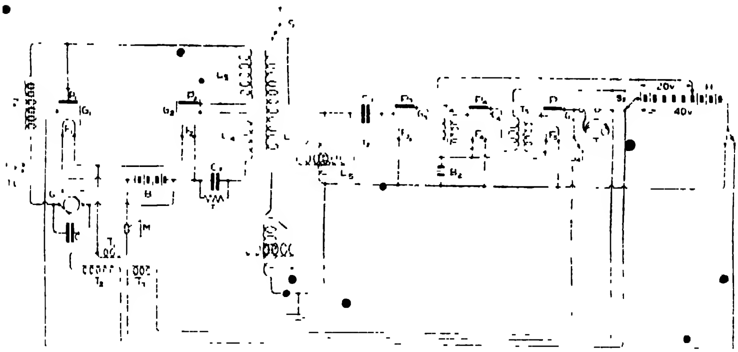


FIG. 319. A 5-watt G.E.C. (U.S.A.) wireless telephone transmitter and receiver.

is placed in series with secondary T_2 of the microphone transformer and gives the grid G_1 of the modulator tube a potential of - 40 volts. The extra "side tone" winding T_3 is connected, when S_4 is closed during transmission, across the telephones T. By this means, the pilot can hear his own voice and so regulate it to obtain the best results. The switches S_1, S_2, S_3, and S_4 are all operated from one change-over switch. An iron filament ballast lamp placed in series with the filaments of the two transmitting tubes was used to maintain a constant filament current.

The Western Electric Company manufactured another (type C.W. 1058) of the standard naval wireless telephones. The circuital arrangements are reproduced in Fig. 320. The transmitting arrangements do not differ essentially from

others that have been described. An iron filament lamp L is included in the filament circuit of the transmitting valves to keep the current constant. No separate grid retroactor coil is provided, but simply a tapping from L_1 which produces a rectroactive effect. The condenser C_6 insulates the positive side of the D.C. generator G from the earth. The motor generator G takes 12 amperes from a 12-volt battery. The set has a range of 18·5 kilometres from aircraft to ground and 9·3 kilometres between two aircraft. The receiver employs impedances Z_1 and Z_2 to couple the vacuum tubes. Switches S_1, S_2 and S_3 are placed in position automatically by a main switch in order to isolate the receiver when transmitting, and *vice-versâ*.

Aircraft Receivers.—One form of American aircraft receiver consisted of a valve acting as a detector and retro-

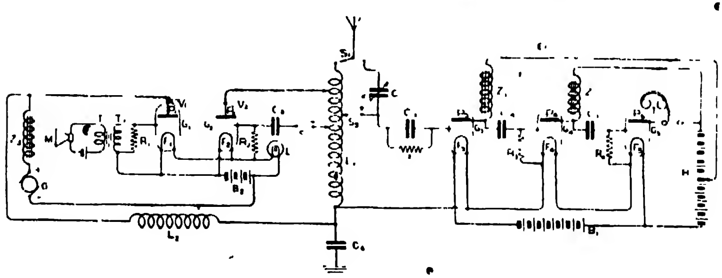


FIG. 320.—A Western Electric Company combined wireless telephone transmitter and receiver.

active amplifier and followed by two low-frequency amplifying tubes coupled by means of iron-core transformers. Another six-stage amplifier used the first three valves as high-frequency amplifiers coupled by air-core transformers, a fourth valve as a detector and two low-frequency amplifying valves employing iron-core transformers.

Duplex Wireless Telephony: some Experiments on its Application to Aircraft.—In a paper read before the Wireless Section of the Institution of Electrical Engineers, P. P. Eckersley has described some very interesting experiments on duplex wireless telephony carried out by himself and R. Whiddington while engaged with the Royal Air Force. The paper conveys much information of general interest, and the reader is advised to consult the original printed paper.*

Elimination of the Carrier Wave.—It may be shown

* *Journal of the Institution of Electrical Engineers*, vol. 58. 293.

that the wave emitted from a wireless telephone installation employing a carrier wave is complex and is built up of three frequencies. If F is the frequency of the carrier wave and f the frequency of the vocal currents set up by the microphone, the emitted wave consists of three frequencies, F, $F-f$, and $F+f$. The unmodulated aerial current F is not needed but may be supplied at the receiving station by a local oscillator. This saves a considerable wastage of energy.

Fig. 321 shows a circuit which has been suggested by Englund, of the Western Electric Co. (U.S.A.), for the elimination of the carrier frequency. A high-frequency generator A, consisting of a vacuum tube oscillator, induces continuous oscillations in the grid circuit L_2T_2 of a modulator vacuum tube V_1, to which circuit is also coupled a microphone M.

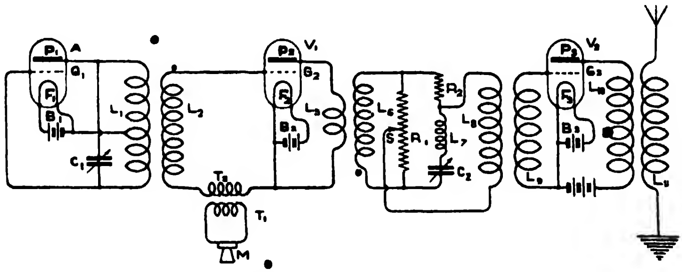


FIG. 321.—Englund's system of eliminating the carrier frequency (anode batteries not shown in case of first two tubes).

Amplified modulated currents are set up in the anode circuit L_5 and are induced into L_6. Anode batteries are not shown in case of first two tubes as the main battery of V_2 may be used.

A special bridge circuit is arranged consisting of resistances R_1 and R_2, an inductance L_7 and condenser C_2. Leads are taken from this bridge to an inductance L_8 coupled to an amplifying system which delivers current to the aerial circuit. The bridge is so adjusted that no currents of the carrier wave frequency can flow in the inductance L_8 but currents differing in frequency upset the balance and flow through L_8. In this way the vocal frequency currents are amplified and passed out to the aerial where they are radiated; no carrier frequency currents, however, are allowed to pass the bridge.

A circuit similar to that of Fig. 322 is used to receive the wireless speech from Englund's circuit. A local oscillator

induces oscillations in the detector circuit of a frequency equal to the original carrier frequency. This arrangement is described by B. W. Kendall and the Western Electric Company in British Patent No. 102500 (Nov. 29/15).

Carson's System of Eliminating Carrier Frequency.— In British Patent 102503 (Dec. 1 15) is described a method of eliminating the carrier frequency invented by J. R. Carson

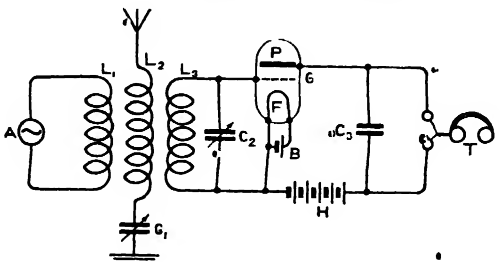


FIG. 322.—Western Electric Company's wireless telephone receiver

for the Western Electric Company. Fig. 323 shows the essentials of the transmitting circuit. A generator A of continuous waves is coupled to the circuit $C_1L_2L_3$. A microphone M with its transformer is likewise coupled to this circuit. The potential across C_1 is the sum of the low or audio-frequency wave, corresponding to variations of transmitter M_1,

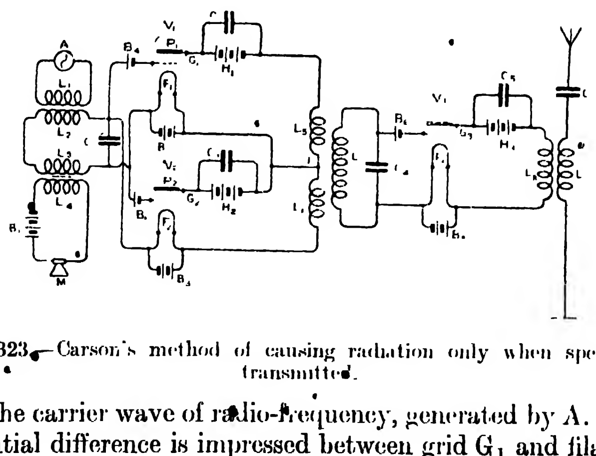


FIG. 323.—Carson's method of causing radiation only when speech is transmitted.

and the carrier wave of radio-frequency, generated by A. This potential difference is impressed between grid G_1 and filament F_1 of the modulator vacuum tube V_1, while an equal potential difference of exactly opposing phase is impressed between grid

G_2 and filament F_2 of a second tube V_2. As a consequence of the potential oscillations impressed between grid and filament of modulators V_1 and V_2, oscillations are developed in circuits L_5 and L_6, these circuits being the output circuits of modulators V_1 and V_2 respectively. The P_1 anode circuit includes a coupling coil L_5, while P_2 anode circuit includes a coupling coil L_6, preferably similar and equal to coil L_5. Coils L_5 and L_6 are so related to coil L_7 of oscillation circuit L_7C_4 that inductive effects due to current oscillations of the same phase in circuits L_5 and L_6 are additive to their inductive action on coil L_7, while current oscillations of opposing phase in circuits L_5 and L_6 oppose and substantially neutralise each other with respect to coil L_7. Circuits L_5 and L_6 may contain condensers whereby they may be tuned to a frequency differing from that of the carrier wave by the mean speech frequency. By means of condenser C_4 circuit L_7C_4 is tuned to this same frequency. Bridged across condenser C_4 is the input side of an amplifier V_3 whose output side is coupled to a transmitting antenna circuit L_9C_6, such antenna including means whereby it is tuned to a frequency differing from that of the carrier wave by the mean speech frequency, that is to the frequency to which circuit L_7C_4 is tuned.

Since voltage oscillations of opposing phase are developed in the input sides of modulators V_1 and V_2, and since output circuits L_5 and L_6, oscillation circuit L_7C_4, and the aerial are tuned to a frequency in the neighbourhood of that of the carrier wave and offer a very great impedance to currents of double carrier wave frequency, the arrangement of Fig. 323 effectually prevents the radiation of the unmodulated carrier wave. It will be further evident that since the component parts of the Fig. 323 arrangement are tuned not to the carrier wave frequency but to a frequency either greater or less than the carrier wave frequency by a frequency approximately equal to that known as mean speech frequency, one of the components of the modulated wave into which the latter is analysable, is transmitted at considerably reduced amplitude as compared with the other components. This discrimination between the components may be made as great as desired in a number of ways such as by increasing the number of oscillation circuits interposed between the modulators and the antenna.

The patent states that the receiving circuit is tuned to the

same frequency as the transmitting aerial of Fig. 323. Preferably several vacuum tubes are used in high-frequency cascade, a local oscillator, generating oscillations of carrier wave frequency, being coupled to the receiving circuits. The patent also describes a duplex system which will be discussed in another paragraph.

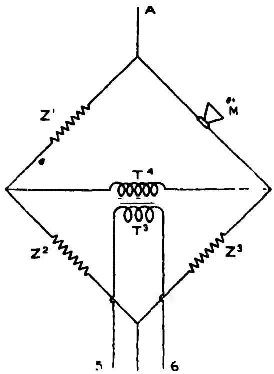


FIG. 324.—Latour's bridge for eliminating the carrier frequency.

Latour's Method of Eliminating the Carrier Frequency.—In British patent application 8318/1918 (Oct. 23/16), Marius Latour describes a high-frequency amplifier in which iron-core coupling transformers are used. He also describes the arrangement shown in Fig. 324. The oscillatory current is applied to the terminals AB of a Wheatstone bridge arrangement consisting of three impedances Z^1, Z^2, Z^3, and a microphone M. A transformer T^4 is connected as shown, the output terminals being 5 and 6. The adjustment may be such that when no one is speaking in front of the microphone, no current passes through T^4. High-frequency energy will only be collected at the terminals 5 and 6 when the microphone is disturbed.

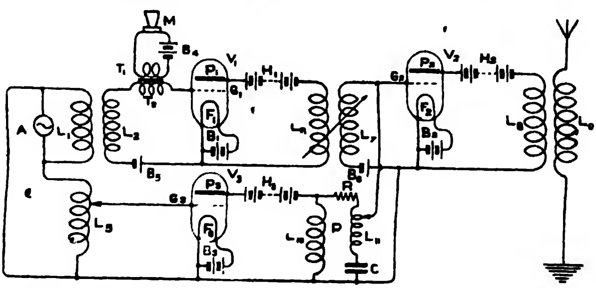


FIG. 325.—Another of Englund's circuits for eliminating the carrier frequency.

The current collected at 5 and 6 may be passed through several amplifiers and then passed out to the aerial.

Another Circuit for Eliminating the Carrier Wave.—Englund has proposed another circuit for eliminating the carrier wave. The general arrangement is shown in Fig. 325.

A high-frequency generator A induces continuous oscillations into the grid circuit L_2T_2 of a modulator tube V_1. A microphone M is also coupled to this circuit. The amplified oscillations in L_6 are of three frequencies, one of which is the carrier frequency. These oscillations are passed on to the grid circuit L_7 of an amplifier tube V_2. The problem is to neutralise the carrier frequency in L_7 so that it will not be amplified by V_2 and radiated from the aerial. It is proposed by Englund to accomplish this in the following manner. The high-frequency currents from the generator A also supply an auto-transformer arrangement L_5. Oscillating potentials are impressed on the grid of an amplifying vacuum tube V_3 in the anode circuit L_{10} of which oscillations of the carrier frequency take place. The

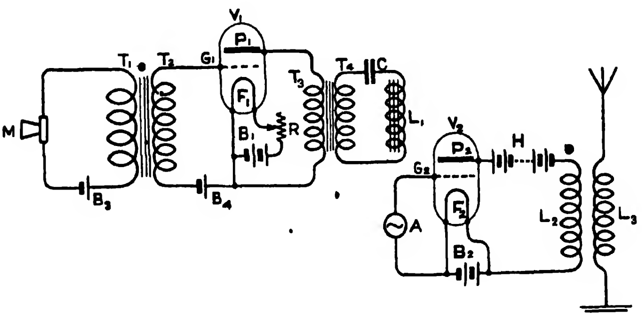


FIG. 326.—Carson's circuit for eliminating the carrier wave.

circuit P, composed of a resistance R, an inductance L_{11}, and a condenser C, is used for phase regulation and by its means oscillations of the carrier frequency are applied to the circuit L_7 in such a way that they are 180° out of phase with the carrier frequency oscillations already taking place in L_7. Since the amplitude of these balancing oscillations may be made equal to the existing oscillations (for example, by means of L_5), the carrier frequency in L_7 may be eliminated and the aerial will only radiate the modulated currents set up when the microphone M is spoken into.

Carson's Proposed Wireless Telephone System.—J. R. Carson has disclosed the wireless telephone system shown in Fig. 326. In this particular system no carrier wave exists, the modulated waves only being transmitted. Consequently when no one is speaking nothing whatever can be heard at the

receiving station. The transmission of a carrier wave involves a serious waste of energy, tends to cause interference, and is a bar to duplex working.

A microphone M is connected as usual in the primary T_1 of a step-up microphone transformer, the secondary winding of which is connected across the grid and filament of an amplifier. A step-up transformer T_3T_4 is connected in the anode circuit of the amplifier. The secondary winding T_4 is connected in series with a condenser C and the field winding L_1 of a radio-frequency alternator. The armature A of the alternator is connected to the input circuit of a high-power amplifier vacuum tube, the anode circuit of which is coupled to the aerial circuit.

When the microphone is spoken into, the magnified microphonic currents pass through the field windings F and cause a high-frequency E.M.F. of varying intensity to appear at the output terminals of the H.F. alternator. These varying potentials are applied to the grid of the second amplifier and a strong modulated high-frequency current is set up in the anode circuit whenever the microphone is spoken into, but not otherwise.

Espenchied Duplex Wireless Telephone Systems.—Several attempts have been made to obtain simultaneous transmission and reception in wireless telephony, so as to reproduce the conditions existing on an ordinary telegraph circuit. It is naturally very inconvenient to have to "change over" whenever it is desired to speak or receive. For the same reason that a pleasant conversation cannot be carried on through a speaking tube, so is it unlikely that wireless telephony will be viewed with favour unless duplex working is possible.

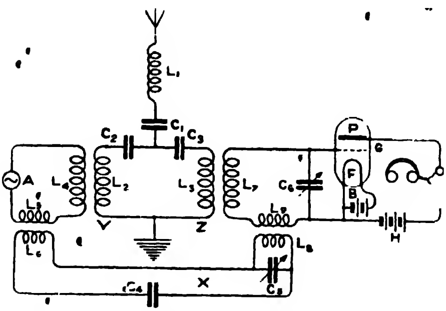


FIG. 327.—Espenchied's duplex wireless telephone system.

Lloyd Espenchied has described several circuits destined to make duplex working possible. Fig. 327 shows the principle of these circuits. The aerial circuit contains inductances and

condensers as shown, there being two parallel branches Y and Z giving the complete system two natural frequencies. The branch Y is coupled to a circuit L_4L_5 which is part of the output circuit of a wireless telephone transmitter. The problem is to get rid of the effect of the powerful oscillations taking place in Y on the receiving branch Z. This is done by using a balancing circuit X which is coupled by L_5L_6 to the radio telephone transmitter. Oscillations are set up in X similar to those in Y and those in Z and the receiving circuit due to the effect of the transmitter. By coupling L_8 to L_9 we induce into the receiving circuit $L_7L_9C_6$ an oscillatory current of exactly the same kind as that induced by Z. By varying the couplings between L_6 and L_5 and between L_8 and L_9,

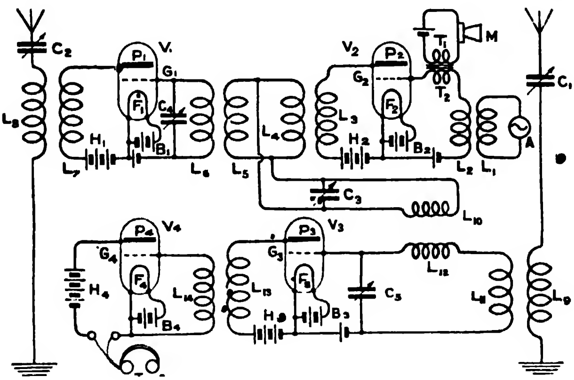


FIG. 328—Espenchied's modified system for simultaneous telephone transmission and reception.

and by adjusting the condensers C_1 and C_5, the two sets of oscillations in $L_7L_9C_6$ may be given a phase difference of 180° and consequently neutralise each other. No oscillatory current due to the transmitter exists in the circuit $L_7L_9C_6$ which can now respond to the incoming telephonic signals of different wave-length. The vacuum tube shown is used in the ordinary way as a detector, though more ambitious circuits could be used.

Espenchied has suggested the use of a vacuum tube amplifier in the X circuit. The winding L_6 is now shunted by a variable condenser and connected across the grid and filament of an amplifying tube. The inductance L_8 shunted by a variable condenser is connected in the output circuit of the

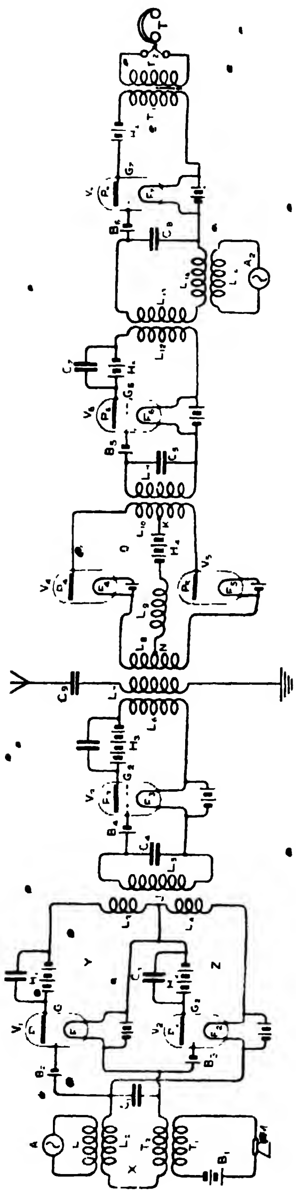


FIG —C W

tube. In this way, a little more latitude of adjustment is provided.

Fig. 328 shows another form of Espenchied's system. In this circuit the current for balancing purposes is not taken from the transmitting aerial circuit but from an intermediate circuit. Any incoming waves received by the left-hand aerial will not find their way to L_{10} since the vacuum tube V_1 acts as a trap. Two valves are shown in use for reception, the first as an amplifier and the second as a detector.

Carson's Duplex Wireless Telephone System.—In British Patent 102503 the Western Electric Company described, as we have seen, a method devised by J. R. Carson for eliminating the carrier frequency. The same patent describes a duplex wireless system which is illustrated in Fig. 329. The left-hand circuit is the transmitting side while on the right-hand is the specially devised receiver. Although both transmitting stations cannot speak at the same time, yet the arrangement allows a rapid interchange of the rôles of transmission and reception.

Suppose, now, that a transmitting station (not shown) is transmitting to the station of Fig. 329. Without the power limiting circuit

associated with V_4 and V_5 destructive amounts of energy would be absorbed by the receiving circuit. This circuit includes two similar thermionic devices V_4 and V_5. The circuit as a whole acts as a power limiting device and by virtue of the tubes the current in this circuit cannot exceed a pre-assigned value depending on the adjustments of these vacuum tubes.

This value is preferably adjusted to approximate equality with that of the signals received from the communicating station. The power limiting circuit, therefore, protects the receiving arrangements from excessive or destructive interference while permitting of the efficient reception of signals.

Simultaneous Radio Telephonic and Telegraphic Transmission.—Englund has devised for the Western Electric

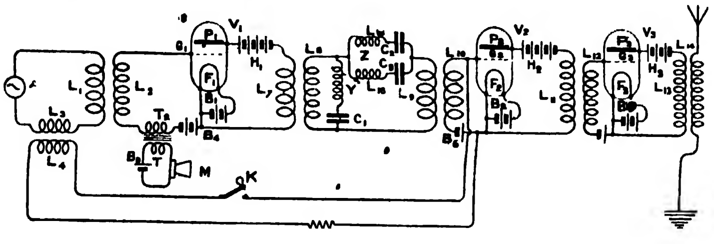


FIG. 330.—Englund's system for simultaneous speech and telegraph trans-

Company (U.S.A.) a circuit suitable for the simultaneous transmission of speech and C.W. telegraphic signals. The essentials of the circuit are reproduced in Fig. 330. A high-frequency generator A supplies the circuit L_1L_3 with continuous oscillations. Oscillating potentials are induced into the grid circuit of the modulator tube V_1. To this grid circuit is coupled a microphone circuit MB_5T, so that the oscillations appearing in L_7 are both magnified and modulated. The oscillations are now passed on to an intermediate circuit which has two branches Y and Z. The branch Y shorts, as it were, the H.F. currents in L_8. The circuit Z has a theoretically infinite impedance to the frequency of the generator while allowing the vocal frequency currents to pass. In this way the carrier frequency is left behind while the vocal frequency is passed on through L_9L_{10} to the grid circuit of the high-power amplifier tube V_2. The amplified currents are now amplified by another

vacuum tube V_3 and then delivered to the aerial. As in all circuits for high power, several vacuum tubes may be connected in parallel when one alone is not able to carry the current.

Now as regards the use of the circuit for ordinary C.W. transmission. The carrier wave is used. The generator frequency currents are induced by L_3 into L_4 and, when the key K is depressed, are conveyed to the grid oscillatory circuit of the amplifier tube V_2. The currents are amplified in the usual manner and passed out to the aerial The resistance R prevents the grid circuit L_{10} of V_2 being shorted by L_4.

By this arrangement there are times when both vocal frequency currents and the carrier wave are superimposed in

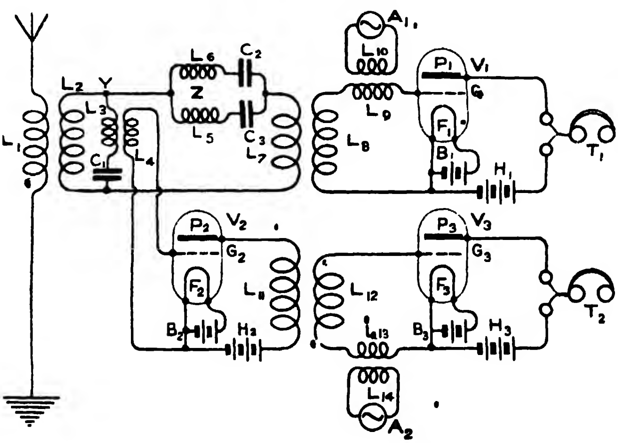


FIG. 331.– Western Electric Company circuit for simultaneous reception of wireless telephone and wireless telegraph signals.

the aerial. Since, in many systems a carrier wave is used, this does not materially affect the quality of the speech at the receiving station.

Fig. 331 shows a receiving circuit for simultaneous telephonic and C.W. reception. Both vocal and carrier wave frequency currents are set up in the secondary circuit, which has two branches Z and Y. The vocal currents pass through Z and L_7 while the carrier wave oscillations pass through Y. The vocal currents are handed on to a detector V_1, a local frequency being provided by the oscillator A_1. The telephonic signals are thus heard in T_1.

The carrier wave signals are passed on from L_3 into L_4, are

amplified by a vacuum tube V_2 and then handed over to a detector V_3, in the grid circuit of which they may be heterodyned by a local oscillator A_2. The telegraphic signals are thus heard in the telephones T_2.

Similar circuits to these are described in British Patent 111649 (Sept. 12/17) by the Western Electric Company.

Breaking-in Systems.—In a simple wireless telephone circuit it is necessary to "change-over" from speaking to receiver. A duplex arrangement is the most useful, but the breaking-in system of Fig. 332 may be of interest. It is

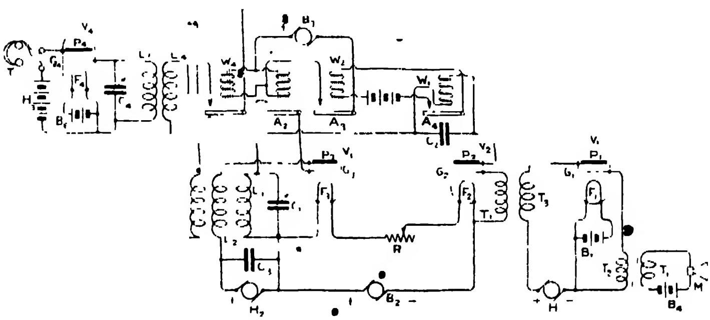


FIG. 332.—General Electric Company's breaking-in system.

described in British Patent 9720/15 (July 3 15) by the General Electric Company (U.S.A.).

Four relays, W_1, W_2, W_3, and W_4 are employed. When the arm A_1 is down, the aerial is connected to the receiving circuit, which uses a detector V_1. When the arm is up the aerial is connected to the aerial inductance L_3 of a C.W. oscillator. This oscillator has an anode circuit L_2 coupled to a grid circuit L_1C_1. The anode potential is supplied by H_2. Across the grid oscillatory circuit is connected a shunt resistance which takes the form of the filament-anode path in the tube V_2. When the transmitter M is spoken into, the voice potentials, amplified by V_1, vary the potential of the grid G_2. A varying amount of energy is thus diverted from the grid oscillatory circuit L_1C_1 through the shunt path F_2P_2, and corresponding variations will be imposed on the amplitude of the waves produced. (This form of modulation is explained in connection with Fig. 304.)

The arrangement appears to work as follows. The source

of filament current B_2 may be connected so that the left-hand side is positive and the right-hand side negative. Consequently the anode P_2, which is connected through W_1 to the left side of B_2, will be positive. A current will flow in the anode circuit of V_2 when the potential of the grid G_2 is altered sufficiently in a positive direction. When the microphone M is spoken into an anode current is set up which passes through W_1 and causes the arm of the relay to touch the contact. This

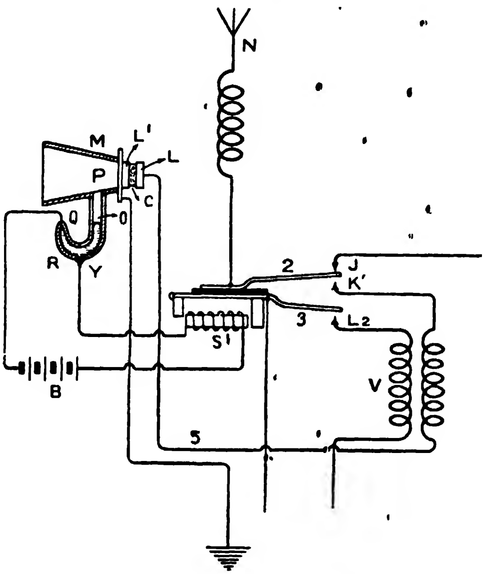


FIG. 333.—De Forest automatic change-over system.

completes the circuit of the relay W_2 and the arm makes contact with the upper contact, thus completing the grid circuit of the generator V_3, which commences to oscillate. When the relay W_2 has operated, the relay W_4 is also brought into action and its arm makes contact with the upper stop, thus switching the aerial on to the transmitting circuit.

When speaking ceases, no current passes to the anode P_2 and the contacts of the relay W_1 separate. The arms of all the relays will drop and the aerial will be changed over to the receiver side.

De Forest's Change-over System.—Lee de Forest describes in British Patent 100841 (July 7/15) an automatic switching

device for use in connection with radio telephone systems. Two arrangements are shown. The second is reproduced in Fig. 333. A capillary tube O opens into the mouthpiece M at P. This tube is preferably U-shaped in length, the end Q being sealed and forming one terminal of the relay S^1. Mercury R is located in the tube O and contact with it is permanently made by a terminal Y. When the microphone M is spoken into, the mercury R rises in the left-hand side of the tube O and makes contact with the terminal Q, thus completing the relay circuit $YRQBS^1Y$. The result is that the armature 3 is made to touch L^2 and the other arm 2, which is insulated from 3, touches K^1. This latter arm connects the aerial through an aerial oscillatory circuit and through the microphone M to the earth. The arm 3 on touching L_2 connects the closed circuit coil V to a source of continuous oscillations.

When speaking ceases the mercury leaves the point Q, the relay circuit is broken and the armature of the relay springs back so that 2 touches J and L_2 is left unconnected. The lead X goes to the aerial terminal of the receiving apparatus, which has a separate earth. Consequently when 2 touches J, the aerial is switched over to the receiving circuit and the source of oscillating current is disconnected.

The other arrangement described in this specification is very similar, the difference being in the microphone. Instead of using a capillary tube, Lee de Forest employs a strip of metal in the microphone; when the microphone is spoken into, this strip makes contact with a screw inside the microphone thus closing the local relay circuit.*

The Dynatron in Wireless Telephony.—A special form of vacuum tube termed a *dynatron* may be used in wireless telephony. A further development of this tube, called a *pliodynatron*, has been used for the wireless transmission of speech, details being given in the next chapter. Other negative resistance devices have also been adapted to wireless telephony.

The present author has produced a number of successful and original modulation systems. In view of the fact that patents have been applied for, it is not possible to give details in the present edition of this volume.

* Neither this nor the previous arrangement are very satisfactory as the beginning of speech is not properly transmitted.

CHAPTER XIV.

THE DYNATRON.

THE "dynatron" is a special form of three-electrode vacuum tube which has been evolved by A. W. Hull of the General Electric Company, of U.S.A. It has been fully described by the inventor in the *Proceedings of the Institute of Radio Engineers* (vol. 6, No. 1, Feb. 1918), and also in British Patents 15555/15, 103865, 114539, 117283, 130400. The reader is referred to these sources for full information. This volume, however, would not be complete without some account of the applications of the device.

Action of Dynatron.—The dynatron consists of a vacuum tube containing a filament surrounded by an anode which may be in the shape of a cylinder with a large number of holes in it; around this anode is a "plate" in the form of a cylinder. The general arrangement is rather similar to that of an ordinary three-electrode tube except in that the anode is close to the plate, whereas in an ordinary vacuum tube the grid is close to the filament. Since the dynatron functions in an absolutely different manner to the ordinary valve, care must be taken not to confuse the actions of the anode and those of a grid.

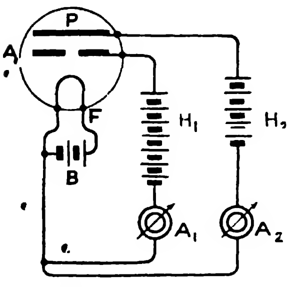


FIG. 334.—Circuit to demonstrate action of dynatron.

Fig. 334 shows a dynatron in a circuit intended to show its action. A battery H_2 maintains the plate P at a positive potential. The galvanometer A_2 measures the plate current. The anode A is close to the plate P and is maintained at a positive potential by the battery H_1. The anode current is measured by the galvanometer A_1.

Normally, the anode A being positive will draw up electrons from the neighbourhood of the filament. If the plate P is at a low potential with respect to the filament many of these electrons will pass through the holes in the anode and will strike the plate P. An electron current will be set up in the plate circuit PH_2A_2F and may be measured by the galvanometer A_2. A certain number of electrons will also go to the anode A and may be measured by the galvanometer A_1.

As we increase the positive potential on the plate (keeping the anode potential fixed), we will increase the flow of electrons to the plate. The plate current will increase. When, however, the plate potential begins to reach a value of about 25 volts the electrons striking the plate attain sufficient velocity to dislodge some of the electrons existing in the plate. By the impact of the *primary* electrons, a new set of *secondary* electrons are knocked out of the plate and wander about near its surface. Under the conditions existing in an ordinary vacuum tube, these secondary electrons would simply return and be reabsorbed by the plate. In the dynatron there is, however, an anode close to the plate and whose potential is made higher than that of the plate. Consequently, the secondary electrons liberated from the plate prefer to go to the anode.

Since the plate is beginning to lose electrons, the plate current will depend on the number of primary electrons entering the plate and also on the number of electrons *leaving* the plate. If 100 million primary electrons during a given period of time are entering the plate when it is at +30 volts, and 50 million secondary electrons are leaving it, obviously the total effect on the plate current will be the same as if 50 million electrons were entering the plate. In general, we can say that the plate current is equal to the electron current entering the plate minus the current leaving the plate. Now the number of secondary electrons liberated from the plate depends on the velocity of the primary electrons; in other words, on the voltage of the plate. By increasing the plate potential we will increase the velocity of the primary electrons, thus increasing the number of *secondary* electrons liberated from the plate. The result is a rapid increase in the number of secondary electrons drawn from the plate. This increase in the number of secondary electrons may be much greater than the increase in primary electrons. Consequently,

the plate current falls in value after a certain value of plate potential. Let us take an imaginary example. By increasing the plate voltage from +30 to +40, the number of primary electrons entering the plate has increased from 106 million to 110 million, but the number of secondary electrons leaving the plate has increased from 50 million to 80 million. The net plate current is that corresponding to 110 million minus 80 million electrons, which equals 30 million as compared to the 50 million flowing in the plate circuit when the plate was at +30 volts.

We thus see that increasing the plate voltage may cause a decrease in the plate current. It will strike the student reader as a curious fact. In an ordinary circuit an increase of E.M.F. causes an increase in current, but here we have a plate circuit possessing *negative resistance*. A circuit possesses *negative resistance* if an increase of E.M.F. across it produces a decrease of current in it, and conversely.

By increasing the plate voltage sufficiently, the number of secondary electrons knocked out of the plate and drawn away by the anode will equal the number of primary electrons entering the plate. Each primary electron is now displacing one secondary electron and the effect will be the same as if no electrons were entering the plate. The plate current will be zero.

If we increase the plate voltage still further, the number of secondary electrodes withdrawn from the plate will exceed the number of primary electrons entering the plate. Consequently instead of there being a zero plate current there will be a plate current in the opposite direction to the usual one. Each electron is now knocking out several secondary electrons from the plate and all these are immediately collected by the anode. In some cases a primary electron is capable of liberating as many as twenty secondary electrons from the plate. As the plate potential is made more and more positive the number of secondary electrons increases and the plate current increases in a reverse direction. The galvanometer A_2 now gives the indication of an electron flow from filament to plate in the *external* circuit.

Earlier on in our explanation we saw that the anode was at a higher potential than the plate and for that reason the liberated secondary electrons went to the anode instead of being reabsorbed by the plate. As, however, we are now

reaching plate voltages almost as great as the anode voltage there is not the same tendency for the liberated electrons to go to the anode and they begin to be reabsorbed by the plate. Consequently the reabsorbed electrons act in the same direction as the primary electrons and the plate current decreases rapidly. As the plate voltage is increased still further, more and more electrons are reabsorbed by the plate and finally the plate current is brought down to zero, the number of electrons now going to the anode being equal to the primary electrons entering the plate.

A further increase of plate potential increases the number of secondary electrons which are reabsorbed, and the number going to the anode becomes smaller and smaller. The plate current is now flowing in the original normal direction, and is due to the primary electrons minus those few secondary electrons which still prefer to go to the anode.

When the plate potential approximately equals the anode potential there is no inducement for any secondary electron to go to the anode. They are all reabsorbed by the plate. As far as they are concerned, the plate current remains the same as if they had never been liberated. The plate current now consists of the sum of the original primary electrons and the reabsorbed electrons *minus* the liberated electrons. Since the number of liberated electrons equals the number reabsorbed the plate current is simply equivalent to the original primary electron current.

Characteristic Curve of a Dynatron.—Fig. 335 shows a characteristic curve of a dynatron. The plate voltage is gradually increased from zero and the plate current is noted and plotted on the vertical axis. The anode voltage is kept constant throughout. Along the portion ABC of the curve the plate current increases in the ordinary way. After the point C has been reached the plate begins to lose secondary electrons rapidly and the total plate current falls. This goes on until the point E is reached. At this point each primary electron dislodges a secondary electron which is carried off to the anode. The number of secondary electrons lost by the plate now equals the number of primary electrons; consequently the resultant effect is zero plate current. If now we increase the plate voltage still further each primary electron will dislodge several secondary electrons and the plate will be losing more electrons than it gains. This is equivalent to

a plate current in the direction opposite to the former direction. After the point G has been passed the device no longer acts as a true negative resistance. The plate current decreases since the anode is unable to carry away all the secondary electrons. The plate current becomes zero once more at the point J and then increases to the point K as the plate reaches the same potential as the anode. The reader is recommended to study the characteristic curve in conjunction with the explanation given in the previous paragraph.

It is to be noted that sometimes the curve does not go below the horizontal axis representing zero plate current. The

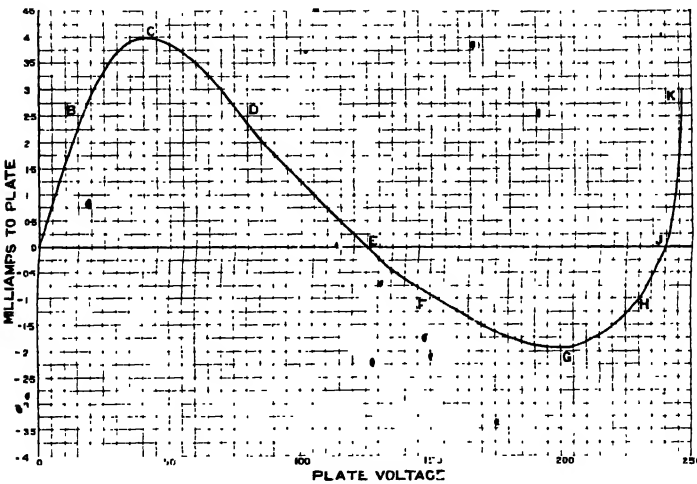


FIG. 335.—Characteristic curve of dynatron.

effect of varying the anode voltage is, in general, to shorten or lengthen the range of the negative resistance part of the curve, without changing the value of the negative resistance. Varying the filament current, on the other hand, changes the negative resistance only, without affecting the range or the operating point. This affords a means of adjusting the negative resistance to any desired value.

Voltage Amplification with the Dynatron.*—The dynatron is capable of being used as a voltage amplifier when the operating point lies on the portion CG of the characteristic curve. If a dynatron is connected in series with a circuit

* A. W. Hull. *Proc. I.R.E.*, vol. 6, 1, 13 (Feb. 1918).

containing a positive or ordinary resistance, the total resistance of the circuit is the algebraic sum of the positive and negative resistances, and may be made as small as desired by making the positive and negative resistances nearly equal. Such a circuit has very interesting properties. For, while the total resistance of the circuit is very small, that of its parts, individually, is not. Hence a small change in the E.M.F. applied to the whole circuit will cause a comparatively large change in current, and therefore in the E.M.F. across each part separately ; *i.e.* the circuit acts as a voltage amplifier.

Let us consider the circuit of Fig. 336. The one battery H serves to give the anode A a suitable positive voltage. A tapping is taken from H to give the plate P a suitable positive potential. This arrangement makes it unnecessary to have two batteries. An ohmic resistance R is connected in series with a dynatron having a negative resistance which may be represented by $\bar{r}$. For the sake of simplicity we will suppose that the dynatron is operating at the point E of its curve (Fig. 335). The plate voltage is now such that the plate current is zero.

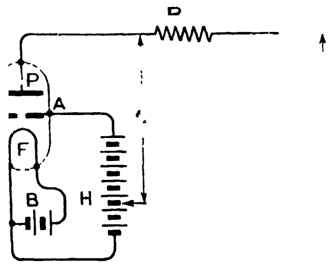


FIG. 336.—To explain voltage amplification by means of a dynatron.

If an electromotive force E be impressed across the combination of R and the dynatron, causing a current I to flow and a voltage drop e_1 in the ohmic resistance and e_2 in the dynatron, then

$$e_1 = \mathrm{IR}$$

$$e_2 = \mathrm{I}\bar{r}$$

Hence $$e_1 + e_2 = \mathrm{E} = \mathrm{IR} + \mathrm{I}\bar{r} = \mathrm{I}(\bar{r} + \mathrm{R})$$

and $$\frac{e_1}{\mathrm{E}} = \frac{\mathrm{R}}{\bar{r} + R}$$

is the ratio of the voltage across the ohmic resistance to the total voltage applied, that is to say the last equation represents the voltage amplification. This can evidently be made as large as desired by making $\bar{r}$ and R nearly equal, since $\bar{r}$ is negative.

With constant batteries, an amplification of 1000-fold can

easily be obtained. For example, if R represents a resistance galvanometer of 2,000 ohms or more, an E.M.F. of 0·01 volt impressed at the terminals of the combination will cause an E.M.F. of 10 volts across the galvanometer, with corresponding amplification of galvanometer current.

The Dynatron as a Current Amplifier.—Since the dynatron is capable of neutralising the resistance of a circuit it will be obvious that an arrangement can be devised having practically no resistance whatever. Fig. 333 shows such an arrangement. If the dynatron is connected in parallel with a circuit containing positive resistance, the total conductivity of the circuit, which is the sum of the positive and negative

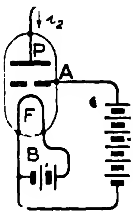


FIG. 337.—The dynatron as a current amplifier.

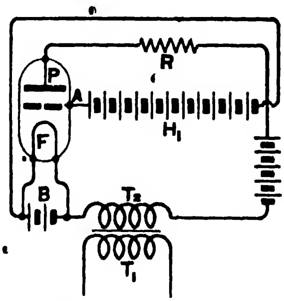


FIG. 338.—The dynatron as a voltage amplifier.

conductivities of its parts, can be made very small. In the circuit of Fig. 337 a current I passes through the combination. This current is made up of a current i_1 through the positive resistance R and i_2 through the dynatron. The current $i_1 = \frac{E}{R}$, while $i_2 = \frac{E}{\bar{r}}$.

Therefore $$I = i_1 + i_2 = \frac{E}{R} + \frac{E}{\bar{r}} = E\left(\frac{1}{\bar{r}} + \frac{1}{R}\right)$$

From this we see that the "current amplification"

$$\frac{i_1}{I} = \frac{\bar{r}}{\bar{r} + R}$$

which may be made very large by making $\bar{r}$ and R nearly equal.

Practical Dynatron Amplifier.—In British Patent 15555/15 (Nov. 4/15), the first of the dynatron patents, the General

Electric Company (U.S.A.) describe the amplifier circuit shown in Fig. 338.

A battery H_1 is employed to impress a constant positive potential upon the anode A. A battery H_2 is also employed with a resistance R in series therewith to impress a positive potential upon the third electrode (the plate) of such a value that the device will operate at a point on the portion GG of the current curve given in Fig. 335. Transformer T_1T_2, the primary winding of which is connected to the source of potential variations which it is desired to amplify, will impress a variable potential upon the circuit. When the connections are made in this way and no potential is supplied by the transformer T_1T_2 a certain definite current will flow in the circuit. When current is flowing there will be a drop of potential through the resistance R and the difference of potential between the cathode and the third electrode will be equal to the difference between this drop and the potential of battery H_2. If the resistance R is greater than the negative resistance $\bar{r}$ of the dynatron and if the additional potential supplied by the transformer T_1T_2 is in the same direction as that supplied by battery H_2, the first effect of the additional potential will be to increase the drop in potential through resistance R and cause the plate to become less positive with respect to the filament. As a result, more current will flow in the circuit. With more current flowing the drop across R increases and the plate becomes less positive, causing a further increase in the current. When a point has finally been reached at which the current becomes stable the charge in the potential difference across the resistance will be much greater than the potential applied by the transformer T_1T_2. The degree of amplification, or the rate of change in potential across the resistance R with changes in the potential applied to the circuit depends upon the ratio of resistance R to the difference between resistance R and the negative resistance $\bar{r}$. The closer these are to each other in value the greater will be the degree of amplification. If the resistance R is less than $\bar{r}$ the same will hold true, and the action will be like that just described, but the effect of the additional potential will be to decrease the drop through resistance R and decrease the current flow. While in the above explanation the current has been considered as reaching its stable value by a series of gradations, it actually reaches that value immediately and

responds to all voltage variations no matter how short their duration. If the extra potential supplied by T_1T_2 is in the opposite direction to that of battery H_2 the action will be just the reverse of that above described.

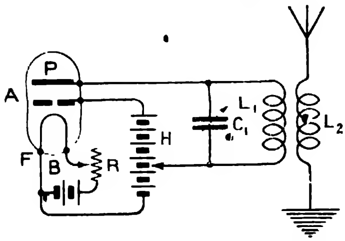


FIG. 339. The dynatron as a generator of continuous waves.

The Dynatron as a Generator.—Practically all negative resistance devices are capable of being used as generators of continuous waves. The ordinary oscillating arc possesses negative resistance characteristics and if an oscillatory circuit be connected across the arc, continuous oscillation will be set up in the circuit.* Similarly if we connect an oscillatory circuit across a dynatron the latter will act as a generator. Fig. 339 shows the dynatron as a generator of continuous waves.

The Dynatron as a Detector.—In British Patent 114539 (June 28 17), another use of the dynatron is given. It is shown in use as a detector, and Fig. 1 of the specification is redrawn here

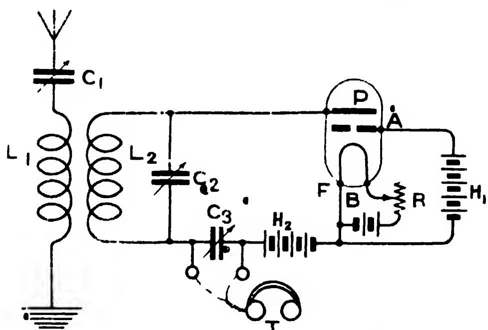


FIG. 340. The dynatron in use as a detector and as a receiver of continuous waves.

as Fig. 340. A positive potential is impressed on the anode A by means of H_1. By varying the potential impressed on the plate P by the battery H_2, the current in the external circuit

* See W. Duddell's Patent 21629/1900 (Nov. 29/1900). He also shows that this property may be used for amplification

L_2T may be made to vary in the manner described in connection with Fig. 335.* It will be seen from this curve that if the potential of the plate is increased up to a value corresponding to the point C or the point G the current, when oscillations are received, will be asymmetric and the device may be used as a detector as well as an amplifier. For the purpose of detecting the signals the usual telephone receiver T, shunted by a variable condenser C_3, is inserted in the plate circuit. The distributed capacity across the turns of the telephone winding offers a low resistance to radio frequencies and hence the telephone does not interfere with the amplification. The high inductance of the telephone, however, will cause the circuit to oscillate at audio frequencies unless its resistance also is very high. The condenser C_3 across its terminals, however, if properly adjusted will prevent the setting up of undesirable audio frequency oscillations.

The dynatron used in this way lessens the damping of the oscillatory circuit L_2C_2 by neutralising the resistance of the circuit. Consequently, much stronger signals are obtained, just as in the case of retroactive amplification. If the damping is made zero the local circuits will oscillate of their own accord at a frequency determined by L_2 and C_2. This frequency may be made to beat with incoming continuous waves and so make the dynatron a suitable receiver of undamped waves.

The G.E.C. state that the dynatron used in the way described above has an important advantage over the usual receiving circuit, namely that the coupling between L_1 and L_2 may be made very close without affecting the selectivity since the necessary condition for high selectivity, namely a small damping factor, may still be present.

The Dynatron as a Compensation for Resistance Losses.† In all oscillatory circuits there is a considerable loss of energy due to the resistance of the circuits. This may be overcome by the correct use of a dynatron. In the patent specification just referred to is another circuit in which the dynatron is used to neutralise the resistance of the grid circuit of a three-electrode vacuum tube.

Another arrangement due to A. W. Hull is given in his

* For complete description of the dynatron see *Physical Review* of Jan. 1916, page 141.

† *Proc. I.R.E.*, vol. 6, 1, 31.

paper. This time, the resistance losses in the *anode circuit* of a three-electrode vacuum tube are compensated for by a dynatron.

A further advantage in this connection is that the dynatron can be operated at such a voltage that its current is just equal and opposite to that of the three-electrode valve, so the total current through the circuit is zero. This allows the use of a more sensitive measuring instrument.

The Pliodynatron.—*Pliodynatron* is the name given to a dynatron which has a control electrode or grid close to the filament. The negative resistance of the pliodynatron, as A. W. Hull states in his paper,* makes it a powerful amplifier. An increase of grid potential, by increasing the current through the load in the plate circuit and hence the voltage drop over the load, lowers the voltage of the plate. In the ordinary three-electrode vacuum tube this lowering of plate voltage tends to decrease the plate current and thus opposes the effect of the grid. In the pliodynatron, however, a decrease in plate voltage means an increase in current, which may be very large if positive and negative resistance are nearly equal. The advantage to be gained in this way may be large, if the resistance in the circuit is high. For example, the maximum voltage amplification thus far obtained with a three-electrode vacuum tube is about 15-fold, while with a pliodynatron in series with a suitable resistance amplifications of 1000-fold have been obtained. To maintain this amplification requires constant batteries and continuous attention. A value of 100-fold is, however, very easy to maintain. By connecting two pliodynatrons in series a total amplification of 10,000-fold has been obtained. The pliodynatron may be used as a detector or for wireless telephony. Numerous circuits are given in A. W. Hull's paper and also in British Patent 117283 (June 2 17).

In British Patent 130400 (Feb. 15 18), the G.E.C. (U.S.A.) describe a modified form of pliodynatron in which a large number of turns of wire are wound round the tube of a dynatron. Modulating currents, such as those from a microphone, produce a magnetic field which causes the electrons to move towards the anode in a spiral path which results in many electrons striking the anode. This form of control is described as being used for wireless telephony. The

* A. W. Hull, *Proc. I.R.E.*, vol. 6, 1, 25 (Feb. 1918).

use of a dynatron in connection with the photo-electric cell is described in British Patent 147149.

An Ordinary Vacuum Tube as a Dynatron.*—An ordinary three-electrode vacuum tube may be employed as a dynatron. Across grid and filament is a potentiometer resistance of several hundred ohms which is connected across a battery or D.C. mains of 100 to 200 volts, the actual value not being material. The anode is connected to the sliding contact on the potentiometer. If an oscillatory circuit be connected between the anode and sliding contact, continuous oscillations will be set up in the circuit if the slider be adjusted to a suitable position. Iron-core and other low-frequency circuits may also be "oscillated" in this manner.

* J. Scott-Taggart and J Ree, *Electrical Review*, Nov. 5, 1920 Also J. Scott-Taggart, *Wireless Age*, Jan. 1921.

CHAPTER XV.

MISCELLANEOUS VACUUM TUBE DEVICES.

Turner Relay.—An interesting "valve relay" has been devised by L. B. Turner. Various forms have been described in British Patent 130408 (Feb. 16 18), and in a paper before the Institution of Electrical Engineers.* One arrangement which will serve as an example is shown in Fig. 341. It has previously been shown that in the case of an ordinary oscillation circuit the oscillatory current depends largely on the grid potential and the position of the operating point on the anode current curve. As this point is brought near the bends the circuit stops oscillating. If now we give the grid a negative potential so that the operating point is well to the left of the lower bend, the system will not oscillate. If, however, we gradually lessen the negative potential of the grid a point will soon be reached, just higher up than the lower bend, where oscillations suddenly commence to be generated. These oscillations, taking place near the lower bend, are rectified by the valve and a large increase of anode current results. This large increase of

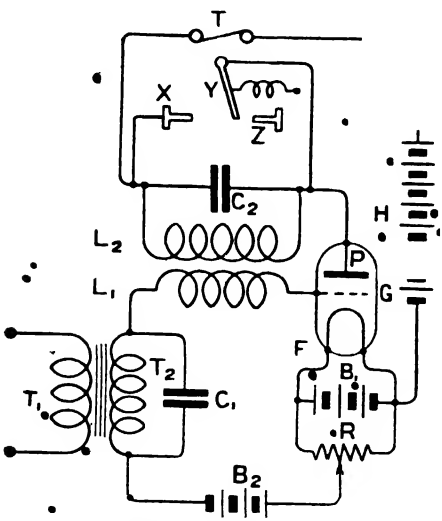


FIG. 341.—Diagram of Turner trigger relay.

* *Journal of Institution of Electrical Engineers*, Supplement to vol. 57, Part 1.

anode current, which is usually one or two milliamps., may be made to operate a relay or sounder or other indicator.' The complete valve relay when adjusted to a point near self-oscillation will be "set off" by about one-fiftieth of a volt acting in a positive direction. The circuit is shown in Fig. 341. The grid coil L_1 is coupled to the anode circuit coil L_2. Oscillations are set up in L_2, C_2 when the incoming signal is fed into the grid circuit by means of the input transformer T_1T_2. The potentiometer across the filament accumulator, and the battery B_2, enable a suitable negative potential to be given to G. It is to be noticed that to enable the valve relay to be worked by Morse signals it will be necessary to bring the valve relay back

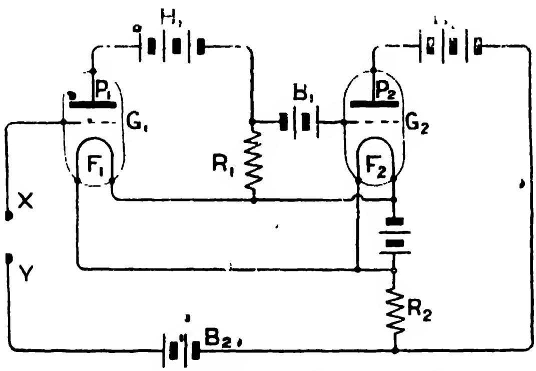


FIG. 312. - Resistance retroaction circuit

to its normal state after each signal. This may be readily done when connecting an ordinary relay T such as is used for telegraph work in the anode circuit of the valve. When the armature of T is attracted over to the left on account of the increase of anode current, it short-circuits the oscillatory circuit L_2C_2 and oscillations cease. The valve relay is now in its normal condition again. The local circuit of the relay is not shown. The present author has suggested placing the relay in the grid circuit. When oscillations commence a grid current of about one milliampere operates the relay.

The Kallirotron and Eccles-Jordan Trigger Relay.—L. B. Turner also claims, in British Patent 139867 (Feb. 17/19), an amplifying device in which two valves are used. The basic idea is illustrated in Fig. 342. It will be seen that two valves are used, coupled by resistances R_1 and R_2 of about

70,000 ohms each. Suppose that a weak E.M.F. is applied to the terminals XY, which are bridged by a conducting input circuit. If this E.M.F. makes G_1 positive, the anode current of the first tube increases. This results in a negative potential being passed on to G_2. This causes a decrease of anode current of V_2. This results in a positive potential at the foot of R_2. This magnified positive potential reinforces the original positive E.M.F. applied to G_1. Large changes in the anode current of the second valve are produced by a building up or species of retroactive action. Batteries B_1 and B_2 are arranged to keep the grid potentials in the neighbourhood of zero volts.

In British Patent 148582 (June 21/18) W. H. Eccles and F. W. Jordan describe an earlier case of a rather similar use

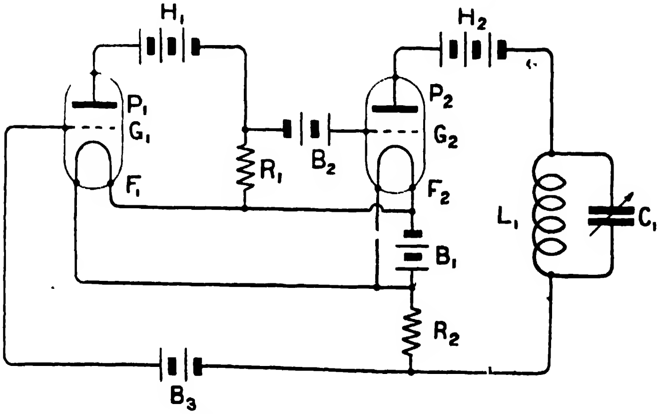


FIG. 343.—The "Kallirotron" oscillator

of two valves to produce a trigger relay effect. The building up effect in this case is not stable, but continues until the anode current of the second valve becomes a minimum, while that of the first valve becomes a maximum. The currents remain like this even after the original impulse (usually applied through a transformer across XY) has ceased. In L. B. Turner's arrangement (called by him the "Kallirotron") the amplification is stable and the anode currents return to their normal value on the cessation of the input E.M.F.*

A valuable development of his circuit is described by

* The relative scope of these two patents has at the time of writing not been decided by the Patent Office.

L. B. Turner. It is an arrangement for the production of oscillations, and is illustrated in Fig. 343. A negative resistance effect is obtained in the anode circuit of the second valve, which results in the production of oscillations which may be used for heterodyne and other purposes. The batteries B_2 and B_3, which are intended to give the grids G_2 and G_1 approximately normal zero potentials by opposing the E.M.F. cross the anode resistances, have been eliminated and only one anode battery is used.

Another negative resistance circuit using two valves and resistances is described by M. Latour in British Patent 148995 (Dec. 16/18).

The "Biotron": A Negative Resistance Device.—The present writer has described in British Patent 152693 (July 25/19) a circuit which is reproduced in Fig. 344. In this circuit the

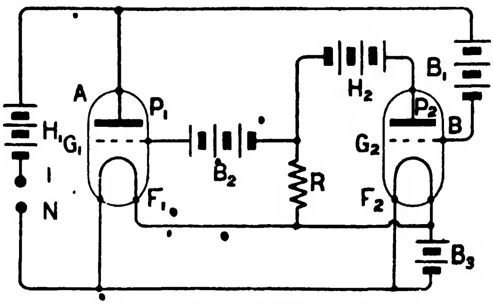


FIG. 344.—The "Biotron" negative resistance device (J. Scott-Taggart).

batteries B_1 and B_2 are used to keep the potentials of G_2 and G_1 in the neighbourhood of zero. Let us assume that the terminals IN are shorted. If we increase the E.M.F. of H, we will increase the potential of P_1. This increase will tend to increase the anode current of the tube A. At the same time, however, the grid G_2 is given a positive potential which increases the anode current of the vacuum tube B. This increase flowing through the high resistance R communicates a *negative* potential to G_1 which tends to decrease the anode current of the tube A. This effect is much stronger than that which tends to increase the anode current of A. The result is that the current in the circuit $P_1H_1INF_1$ decreases when the E.M.F. of H_1 increases. In other words the circuit possesses negative

resistance characteristics, and if a circuit having positive resistance be inserted across IN, this positive resistance may be neutralised. The circuit may be utilised for numerous purposes, as an amplifier, generator of oscillations (in which case an oscillation circuit is inserted between I and N), and detector.

The "Negatron": A Negative Resistance Valve.—The present author has invented a new vacuum tube which possesses negative resistance characteristics. Its applications as an oscillator, amplifier, detector, etc., are comparable to those of the Dynatron while working on an entirely different principle. As the patents for this valve have not been published at the time of writing, it is not possible to give details in this volume.

CHAPTER XVI.

RECENT DEVELOPMENTS.

A METHOD of receiving wireless signals due to N. P. Hinton, B.Sc., is of considerable interest.

Fig. 345 shows a simple receiving system in which a rejector circuit is used. The rejector circuit is marked L_3C_3, while the circuit L_2C_2 is an acceptor circuit. The circuit L_3C_3 is tuned to the frequency of the incoming signals, which are to be received, and the circuit will therefore reject that particular

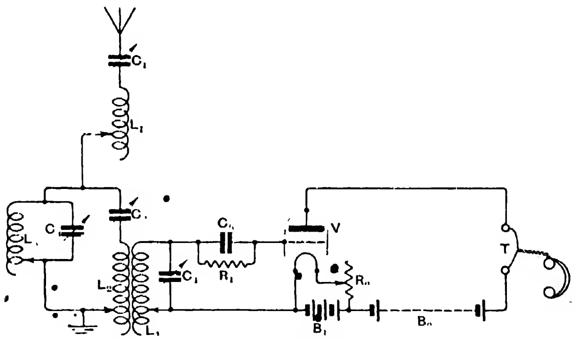


FIG. 345. A simple parallel rejector circuit.

frequency. The circuit, however, will not reject interfering frequencies which therefore pass through it. The inductance L_3 is usually of very small value.

Fig. 346 shows the application of the Hinton system to such a circuit. The rejector circuit L_3C_3 now has its damping reduced to almost zero by means of a valve V, while the ordinary receiving circuit $L_4C_4DC_5T$ is associated with the inductance L_2 in the acceptor limb of the aerial circuit. The reaction between L_5 and L_3 is so adjusted that the valve V is

on the verge of oscillation. Under these conditions, when the circuit L_3C_3 is tuned to the desired incoming signals very great selectivity is obtained.

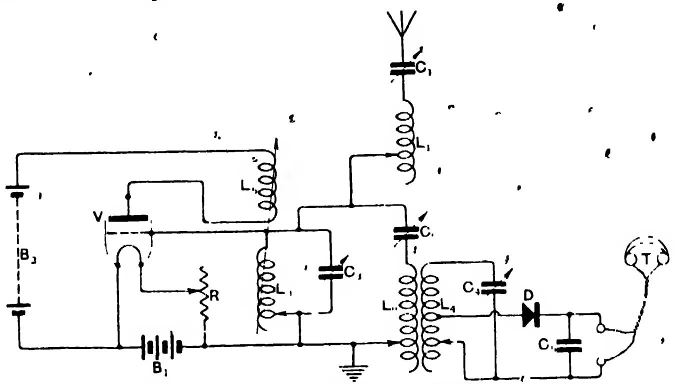


FIG. 346.—A parallel rejector circuit using reaction.

Fig. 347 shows the practical circuit which has been extensively used by the British Post Office. In this case the circuit L_3C_3 is connected in parallel with the closed circuit L_2C_2, and the reaction coil L_6 is coupled to the inductance L_3.

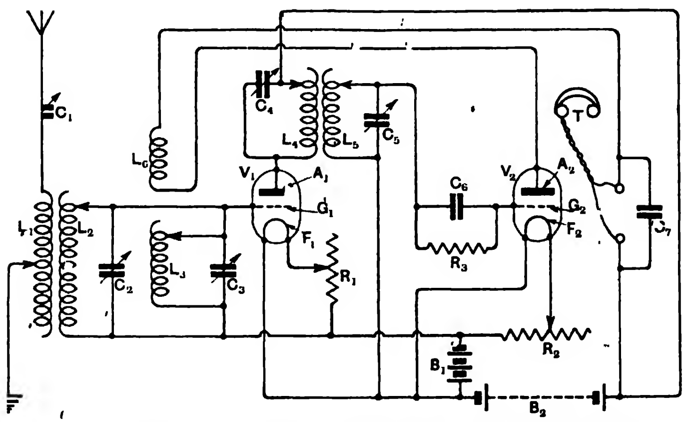


FIG. 347.—A receiver employing a parallel rejector circuit with reaction.

The Hinton receiving method is also generally applied to low-frequency circuits when continuous waves are being received. Fig. 348 shows a low-frequency amplifier in which a low-frequency rejector circuit T_3C' is employed. This circuit

is connected in parallel with the telephone receivers T and acts as a short circuit for all frequencies other than the desired note. This note is rejected by the circuit T_3C, and therefore

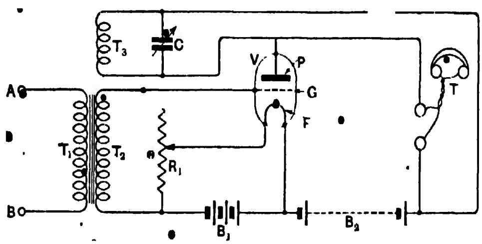


FIG. 348. A low-frequency rejector circuit.

passes through and operates the telephones T. Notes of other frequencies, however, pass through the inductance T_3, and this circuit therefore acts as a short circuit for these frequencies.

Fig. 349 shows a complete receiving system in which both

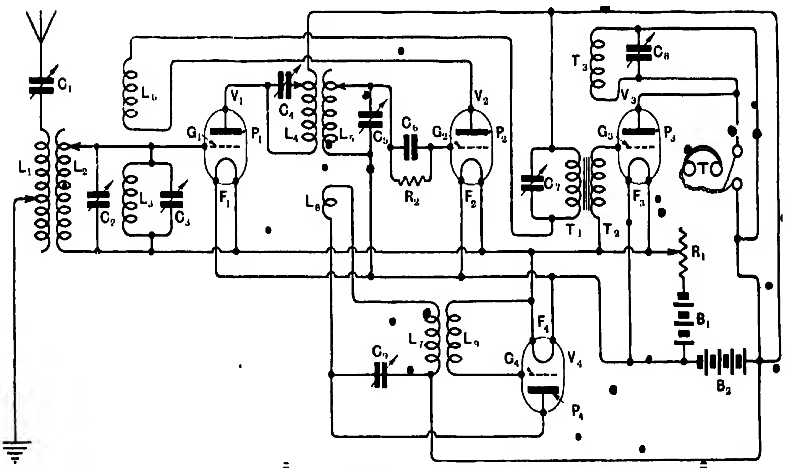


FIG. 349. A complete receiver using radio- and audio-frequency rejector circuits.

high- and low-frequency rejector circuits are employed. The set is remarkably effective.

Double Reaction.—A useful circuit which, in some cases, is found to give appreciably louder signals, has been used by the writer and is reproduced in Fig. 350. In this circuit reaction is introduced from the anode circuit of the second

valve on to the tuned anode circuit L_2C_2, and also on to the aerial circuit L_1C_1.

A Special Valve.—H. P. Donle has published a description of a vacuum tube which is stated to be exceedingly sensitive,

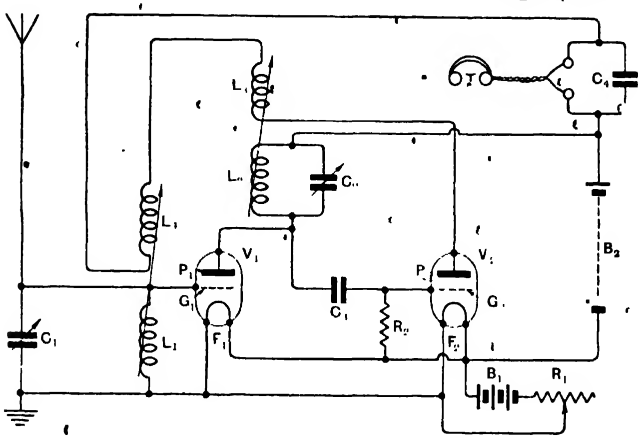


FIG. 350. Reaction is applied to the aerial circuit and the rejector circuit by two reaction coils connected in series.

and which operates effectively as a rectifier. This tube contains an anode in the form of metallic sodium in the bottom of a tube. An ordinary filament is used and the control electrode is the grid C consisting of a semicircular metallic plate.

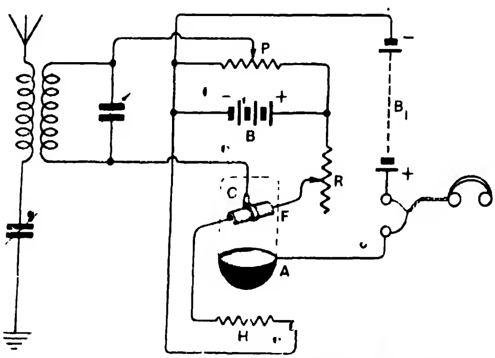


FIG. 351. Circuit of the new rectifier tube. Note the resistance in series with the filament. The current consumption is about the same as that of a standard tube.

A heater wire H in Fig. 351 is for the purpose of warming the sodium.

Two Interesting Dual Amplification Circuits.—Two dual amplification circuits which have been described by the present writer, and which have achieved very great success, are described below.

The first is illustrated in Fig. 352. It will be seen that the first valve acts as a high-frequency amplifier with reaction and also as a low-frequency amplifier. The second one acts as a low-frequency amplifier alone.

A resistance R of 100,000 ohms resistance is connected across the grid and the positive side of the filament accumulator. The purpose of this resistance is to stabilise the circuit and to prevent howling.

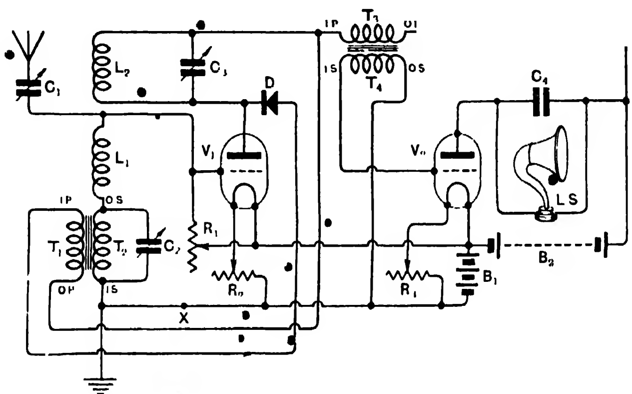


FIG. 352.—A practical dual-amplification circuit.

Another dual amplification circuit is shown in Fig. 353. In this case the first valve acts as a high-frequency amplifier, and is coupled to the second valve by means of a tuned anode circuit. The second valve, in this case, acts as the detector, whereas in the preceding circuit a crystal detector was employed for that purpose. In the anode circuit of the second valve we have a reaction coil L_3 which introduces reaction into the tuned anode circuit, and also the primary of a step-up intervalve transformer, the secondary of which is included in the grid circuit of the first valve which acts as a low-frequency amplifier as well as a high-frequency amplifier. Signals obtained with this circuit are very good, and, if desired, an additional valve used as a low-frequency amplifier may be added. In this case the primary of a step-up intervalve

transformer is connected in place of a loud speaker shown in the circuit.

Both these circuits may be modified by the addition of low- or high-frequency stages of amplification.

The Armstrong Super-Regenerative Circuit.—A type of circuit which has had a considerable vogue is that commonly known as the Armstrong super-regenerative circuit. This circuit takes many forms, but the principle, briefly, is that the reaction effect is increased beyond the stage which ordinarily is the limit before self-oscillation commences. Self-oscillation

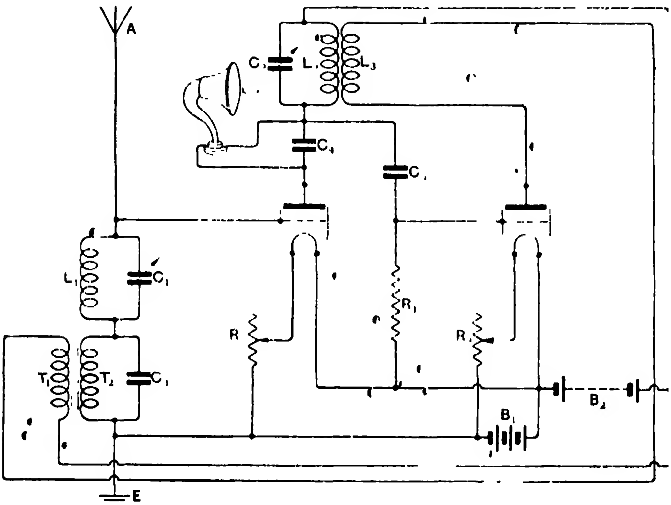


FIG. 353.—A reflex circuit employing valve rectification.

is actually prevented by introducing damping at a medium frequency which may be 5000 times per second. This damping may be introduced by a valve oscillating at semi-low-frequency and varying the grid potential of the valve which produces the reaction.

The following description is taken from a Paper by E. H. Armstrong, read before the Institute of Radio Engineers.

Before proceeding with a description of this method, it is in order to consider a few fundamental facts about regenerative circuits. It is well known that the effect of regeneration—that is, the supplying of energy to a circuit to reinforce the oscillations existing therein—is equivalent to introducing a

negative resistance reaction in the circuit, which neutralises positive resistance reaction, and thereby reduces the effective resistance of the circuit. There are three conceivable relations between the negative and positive resistances—namely, the negative resistance introduced may be less than the positive resistance, it may be equal to the positive resistance, or it may be greater than the positive resistance of the circuit.

We will consider what occurs in a regenerative circuit containing inductance and capacity when an alternating electromotive force of the resonant frequency is suddenly impressed for each of the three cases. In the first case (when the negative resistance is less than the positive), the free and forced oscillations have a maximum amplitude equal to the impressed E.M.F. over the effective resistance, and the free oscillation has a damping determined by this effective resistance. The steady state is attained after the initial free oscillation dies out and continues until the impressed E.M.F. is removed, when the current dies out in accordance with a second free oscillation. The maximum amplitude of current in this case is always finite: it reaches this maximum amplitude in a finite time, and when the impressed E.M.F. is removed the current dies away to zero. This is the action of the circuits which are now in everyday practical use.

In the second case the negative resistance is equal to the positive resistance, and the resultant effective resistance of the circuit is therefore zero. When an E.M.F. is suddenly impressed in this case the current in the circuit starts to increase at a rate which is directly proportional to the impressed E.M.F. and to the square root of the ratio of the capacity to the inductance of the circuit (for a given impressed frequency). If the E.M.F. is impressed for an infinite time, then the current in the circuit reaches infinity. If the E.M.F. is impressed for a finite time, then the current reaches some finite value. When the impressed E.M.F. is removed, the current in the circuit at that instant continues indefinitely with unchanged amplitude as a free oscillation. Theoretically, this is the limiting case for regeneration; practically, it is always necessary to operate at some point slightly below this state at which the circuits have a definite resistance.

It is important to note here that although the circuit of this case has zero resistance, oscillations will not start unless an E.M.F. is impressed upon the circuit; furthermore, that

oscillations once started continue with undiminished amplitude indefinitely. This state cannot be attained in practice, because the negative resistance furnished by the tube is dependent on the amplitude of the current and for stable operation decreases with increasing amplitude.

In the third case the negative resistance introduced into the circuit is greater than the positive resistance, and the effective resistance of the circuit is therefore negative. When an E.M.F. is impressed upon a circuit in this condition, a free and forced oscillation are set up which have some interesting properties. The amplitude of the forced oscillation is determined by the value of the impressed E.M.F. divided by the resultant resistance of the circuit. The free oscillation starts with an amplitude equal to the forced oscillation and builds up to infinity regardless of whether or not the external E.M.F. is removed. This free oscillation starts with an amplitude which is proportional to the impressed E.M.F., and this, proportionally, is maintained throughout any finite time interval, with the constant impressed electromotive force.

It is important to note that although the negative resistance of the circuit exceeds the positive, and the effective resistance of the circuit is negative, oscillations will not occur until some E.M.F. is impressed. However, no matter how small it may be, the current in the circuit builds up to infinity regardless of whether or not the external E.M.F. is removed.

The fundamental difference between the case in which the resistance of the circuit is negative may be summed up as follows: In the first, forced oscillation contains the greatest amount of energy, and the free oscillation is of very minor importance (after a short interval of time); in the second it is the free oscillation which contains the greatest amount of energy, and the forced oscillation which is of negligible importance.

It is, of course, impossible with present-day instrumentalities to set up a system in which the negative resistance exceeds the positive without the production of oscillations in the system, since any irregularity in filament emission or impulse produced by atmospheric disturbances is sufficient to initiate an oscillation which builds up to the carrying capacity of the tube. It is, however, possible by means of various expedients to set up systems which avoid the production of such a paralysing oscillation, and which approximate

the theoretical case in the use of a free oscillation to produce amplification.

It is the purpose of this account to describe a principle of operation based on the free oscillation which is quantitative and without a lower limit. This new method is based on the discovery that if a periodic variation be introduced in the relation between the negative and positive resistance of a circuit containing inductance and capacity in such manner that the negative resistance is alternately greater and less than the positive resistance, but that the average value of resistance is positive, then the circuit will not of itself produce oscillations, but during those intervals when the negative resistance is greater than the positive, will produce great amplification of an impressed E.M.F. The free oscillations which are set up during the periods of negative resistance

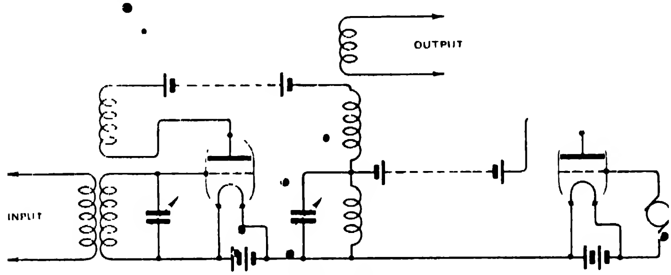


FIG. 354.

are directly proportional in amplitude to the amplitude of the impressed E.M.F. The variation in the relation between the negative and positive resistance may be carried out by varying the negative resistance with respect to the positive, by varying the positive resistance with respect to the negative, or by varying both simultaneously at some frequency which is generally relatively low compared to the frequency of the current to be amplified.

These three methods of producing the super-regenerative state are illustrated by Figs. 354, 355, and 356, which figures indicate the general scheme of the system and the methods varying the relation between the negative and positive resistance. Fig. 354 shows a method of varying the negative resistance produced by the regenerative system by varying the voltage of the plate of the tube by means of a second tube, the grid of the second tube being excited by an E.M.F. of

suitable frequency. Fig. 355 illustrates a method of varying the positive resistance of the circuit with respect to the

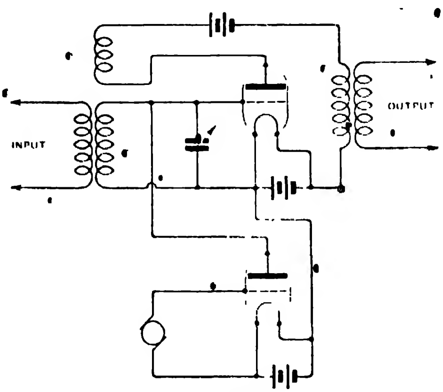


FIG 355.

negative. This is accomplished by connecting the plate circuit of a vacuum tube in parallel to the tuned circuit of the regenerative system and exciting the grid by an E.M.F. of suitable frequency. Fig. 356 illustrates a combination of

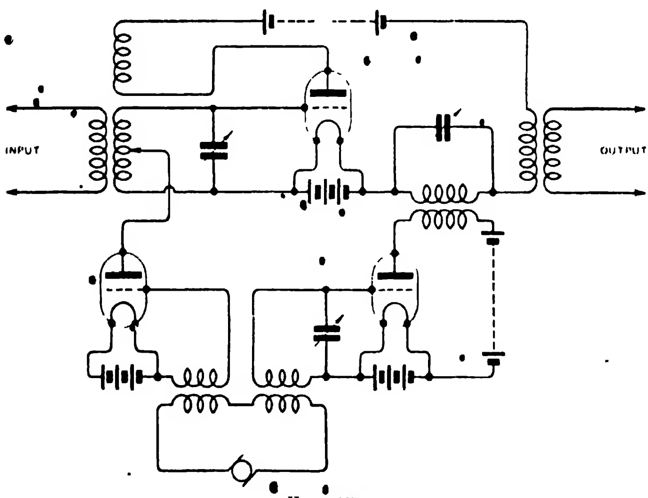


FIG 356

these two systems in which simultaneous variations are produced in both the negative and positive resistances and

provision made for adjusting the relative phases of these two variations.

A general idea of the phenomena occurring in these systems when an E.M.F. is applied to input circuit will be obtained from the diagram of Fig. 357, which applies specifically to the circuit of Fig. 354. This figure illustrates the principal relations existing in the system in which the positive resistance is constant and the variation is introduced into the negative resistance. It will be observed that the frequency of variation appears as a modulation of the amplified current so

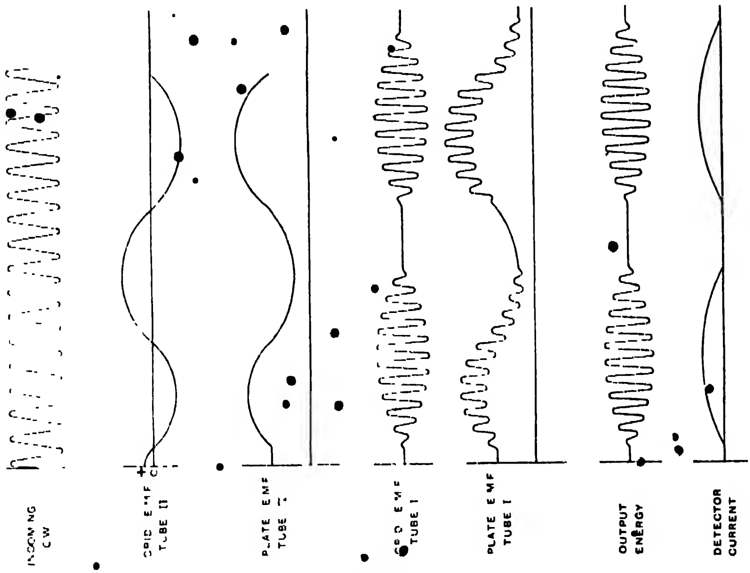


FIG. 357.

that the output current contains currents of the impressed frequency plus two side frequencies differing from the fundamental by the frequency of the variation.

Oscillograms of the essential current and voltage relations existing in the systems of the type illustrated by Figs. 354 and 355 were obtained with the set up of apparatus illustrated in Figs. 358 and 359 respectively. In the arrangement of Fig. 359, in order to produce sufficient variation in the positive resistance of the tuned circuit, which was of large capacity and low inductance, it was necessary to use a two-electrode tube in series with the auxiliary E.M.F.

Two oscillograms respectively for a negative resistance variation and a positive resistance variation with the signalling E.M.F. impressed about half-way along the film, the exact

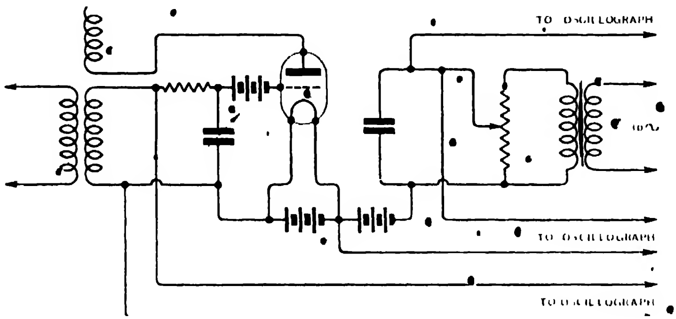


FIG 358.

point at which the key was closed being indicated by an arrow, show phenomena which are in accordance with the explanations already given, but in addition show evidence of self-excitation. It has been stated in the preceding pages of this

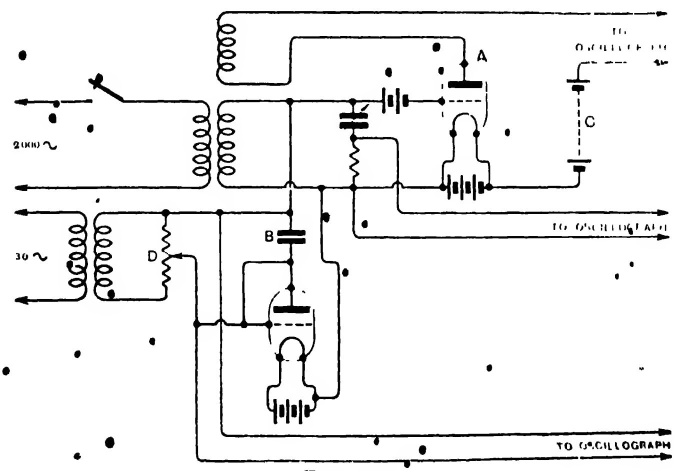


FIG 359.

account that the basis of super-regeneration was the discovery that a variation in the relation between the negative and positive resistance prevented a system which would normally

oscillate violently from becoming self-exciting. An examination of the oscillograms will show that this is not strictly true, as a free oscillation starts every time the resistance of the circuit becomes negative. It will be observed, however, that this free oscillation is small compared to that produced by the signal, and therein lies the complete explanation of the operation of the system. The free oscillations produced in the system when no signalling E.M.F. is impressed must be initiated by some irregularity of operation of the vacuum tubes and must start at an amplitude equal to the amplitude of this disturbance. This initial value is of infinitesimal order and hence, in the limited time interval in which it can build up the locally excited oscillation, never reaches an amplitude comparable to the oscillation set up by a signal of any ordinary working strength.

There is a second point of interest which is most evident from the oscillograph curves. There is a decided lag in the maximum value attained by the free oscillation set up by a signal and the maximum value of plate voltage (negative resistance) of the amplifying tube. This is most evident from the plate current curve. It is a point of considerable interest, and the phenomena involved will be analysed in a later part of this Chapter.

The rate of variation in the relation between the negative and positive resistance is a matter of great importance. It may be at sub-audible, or super-audible, or audible frequencies. In radio signalling for the reception of telephony, the variations should be at a super-audible frequency. For modulated continuous wave telegraphy and spark telegraphy, to retain the tone characteristics of the signals, it must be well above audibility; for maximum amplification a lower and audible rate of variation should be used. In continuous wave telegraphy, where an audible tone is required, the variation is at an audible rate; where the operation of an indicating device is required a sub-audible frequency may be best. The choice of frequency is a compromise, particularly in telephony, since obviously the lower the frequency the greater the amplification, and the higher the frequency the better the quality.

Some practical forms of circuits are illustrated by Figs. 360, 361, and 362, which illustrate respectively the three types of variation. Fig. 360 shows a method of varying the plate voltage coupled into the plate circuit. In this arrangement

a third tube acts as a detector. This is essential when an

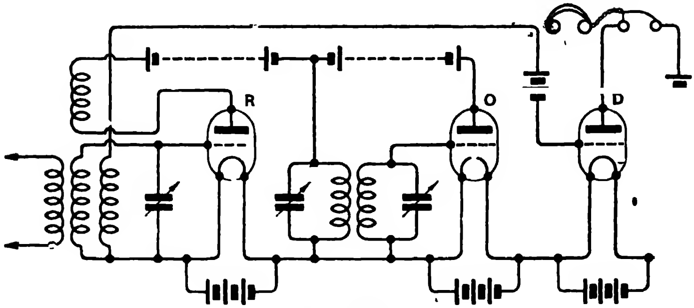


FIG. 360.

audible frequency is employed : when a super-audible frequency

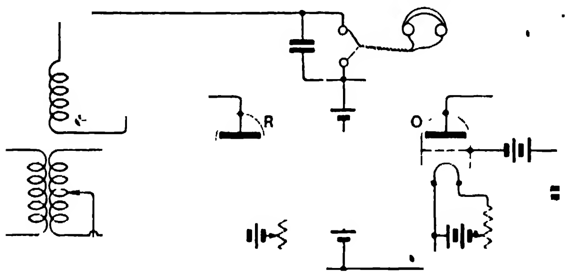


FIG. 361.

is used the telephones can be placed directly in the plate circuit of the amplifying tube.

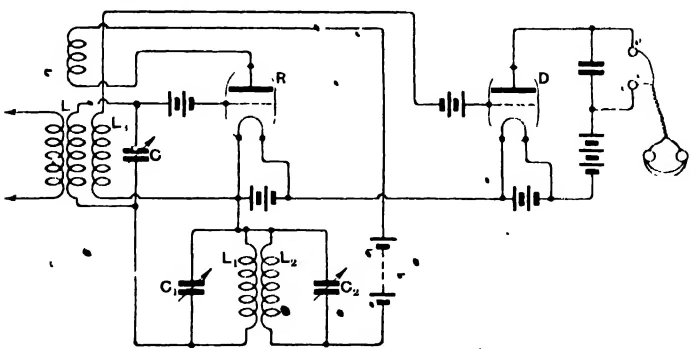


FIG. 362.

Fig. 361 shows the second case in which the variation is

introduced into the positive resistance of the tuned circuit. This is done by means of an oscillating tube O, the grid circuit of which is connected through the tuned circuit LC of the amplifying tube R. The variation in the resistance of the circuit is effected through the variation in potential of the grid of the oscillating tube. During that half of the cycle, when the grid of the oscillating tube is positive, energy is withdrawn from the tuned circuit in the form of a conduction current from the grid to the filament of the oscillating tube, thereby increasing the effective resistance of the circuit. During the other half of the cycle, when the grid of the oscillating tube is negative, no conduction current can flow through the grid circuit of the oscillating tube, and hence no resistance is introduced into the tuned circuit of the amplifying tube. In this case the amplifying tube serves also as the detector for any frequency of variation, as the tuned circuit forms a sufficiently good filter even for an audible frequency to prevent a disturbing audible tone in the telephones. Fig. 362 illustrates the case of a simultaneous variation in both positive and negative resistance. This is accomplished by providing the amplifying tube R with a second feed-back circuit L_1C_1 and L_2C_2, adjusted to oscillate at some lower frequency, thereby introducing a variation in the negative resistance through the variation of the plate potential of the amplifier and a variation in the positive resistance by means of the variation of the grid of the amplifier. The proper phase relations between the negative and positive resistance are obtained by adjustment of the capacity of condensers C_1 and C_2, and the coupling between L_1 and L_2. In operation this system is very critical, and extreme care is necessary in order to obtain the super-regenerative state.

In each of the preceding cases the detecting function has been carried out either by a separate tube or by means of the amplifying tube. When a super-audible frequency of variation is employed, it is sometimes of advantage to perform the detecting function in the oscillating tube, and a system for carrying this out is illustrated in Fig. 363. The operation of this system is as follows: Incoming signals are amplified by means of the regenerative action of the amplifier tube R, and the variations of potentials across the tuned wave frequency circuit LC impressed upon the grid of the oscillating tube O. These oscillations are then rectified and two frequencies are produced

in the circuits of the amplifier tube. One of these frequencies corresponds to the frequency of modulation of the signalling wave. The other corresponds to the frequency of the variation, and contains a modulation in amplitude corresponding to the modulation of the transmitted wave. This second frequency is then impressed upon the circuits of the oscillating tube with which it is in tune, amplified by the regenerative action of the system $L_1C_1L_2O$, and then rectified. The amplification obtainable with this form of system is considerably greater than that of the single amplification circuits, but is naturally more complicated to operate.

When a super-audible variation is employed in a system

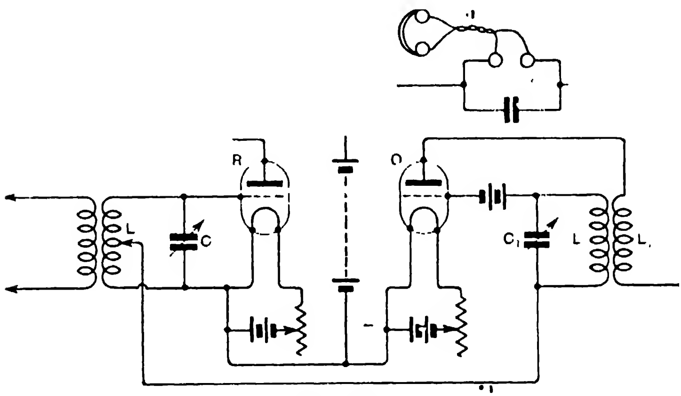


FIG. 363.

such as illustrated in Fig. 354 it is generally necessary to introduce a certain amount of resistance in the tuned circuit to ensure the dying out of the free oscillation during the interval when the resistance of the circuit is positive. This is most effectively carried out by means of the arrangement illustrated in Fig. 364, in which a secondary coil L_1 of large inductance and high resistance is coupled to the tuned circuit LC and the energy withdrawn thereby from the oscillating circuit stepped up and applied to the grid of the tube. In the operation of this system a curious phenomenon is encountered. This is the manifestation of an inductive reaction by the plate circuit of the amplifying tube to the auxiliary frequency E.M.F. supplied the plate circuit by the oscillating tube. This comes about in the following way: When the

auxiliary E.M.F. is impressed upon the plate of the amplifying tube, a current is produced in this tube in phase with the E.M.F. across the tube. Now suppose the plate voltage is at its maximum positive value. This means that the negative resistance of the circuit is a maximum in amplitude. This in turn means that the average value of the grid is becoming more positive and the current in the plate circuit is likewise increasing. Since the free oscillation in the system will increase in amplitude as long as the resistance of the circuit is negative, it will reach its maximum amplitude after the maximum positive voltage is applied to the plate. Hence the component of current corresponding to the frequency of the variation set up in the plate circuit by the rectification of the radio-frequency

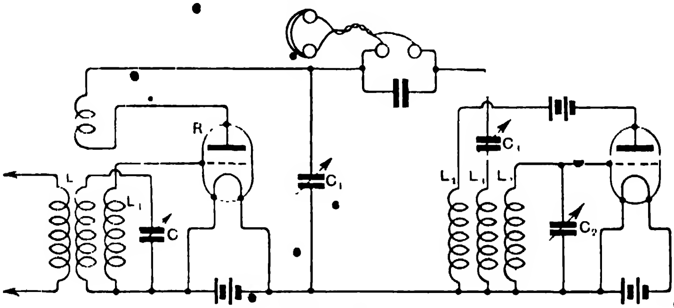


FIG. 364.

oscillations lags in phase behind the auxiliary E.M.F. impressed on the plate. Hence the plate circuit of the tube manifests an inductive reaction to the auxiliary E.M.F. It was found that this inductive reaction could be tuned out by means of the parallel condenser C_1 with the great improvement in the stability of the operation of the system and increase in the signal strength. The resonance point is pronounced, and once the other adjustments of the system have been correctly made is as readily found as any ordinary tuning adjustment.

The Negatron.—The negatron, one of the present author's inventions, is a thermionic tube having two flat anodes, one on each side of a filament. Each anode is connected through an anode battery to the filament so that the electrons emitted by the filament, when it is heated to incandescence, are distributed fairly equally between the two anodes. A control electrode, which may be a flat grid (or

sometimes a straight wire acting as a grid), is also arranged within the tube between the filament and one of the anodes. This latter anode will be called the "diversion anode," while the first one will be called the "main anode." If we suitably arrange the relationship between the electron emission and the anode voltages, we may make the sum of the two anode currents approximately equal to the electron emission. In other words, a saturation effect is obtained. Under these conditions, if we make the grid more positive with respect to the filament, we shall divert electrons from the main anode to the diversion anode, with a consequent reduction in the current flowing in the main anode circuit. In the negatron as preferably used, the main anode is connected to the grid so that when the main anode voltage is increased the grid potential is increased, electrons are diverted from the main anode, and the main anode current decreases. Hence the negative resistance effect.

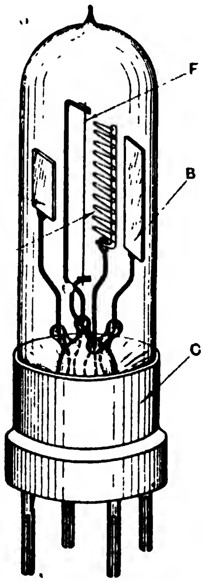


FIG. 365. - A form of negatron valve having a zig-zag wire grid; the control electrode's usually simply a single vertical wire.

Fig. 365 illustrates the negatron tube itself. The anode on the left is the main anode (usually small), while the anode on the right is the diversion anode. Between the filament and the diversion is a flat open-work grid. A tubular bulb with a four-pin cap is preferred, the connection to the main anode being taken to the metal portion of the tube cap. A metal spring on the holder presses against and makes electrical contact with this metal portion.

The action of the negatron will be best understood if reference is made to Fig. 366, which shows a negatron connected up in one way so as to possess negative resistance characteristics. Between the anode A and the filament F is a battery B_3 and two terminals IN. Between these terminals a milliameter may, for the time being, be connected. The anode A is connected through a battery B_5 to the grid G. This battery is merely connected in this position to keep the

grid at a suitable potential, which is preferably slightly negative. If G were connected directly to A, G would have a high positive potential with respect to F. Between F and the diversion anode B is a second battery B_2. Both B_3 and B_2 are usually of about 60 volts, but their values are not very important provided that the current supplied to the filament F may be adjusted to produce the saturation effect.

Let us now see what will happen if we increase the voltage of B_3. We should normally expect the current to A to increase, but as the potential of A increases so does that of the grid G. Since G becomes more positive, the current to B will increase, and this increase could be measured by connecting a second milliameter in the B anode circuit. This method of varying the current to B is, of course, well known, as it has been used in ordinary tubes since the grid was first introduced. The important fact to notice, however, is that if the current to B increases, the electrons which go to B must come from those which would have gone to the anode A. There is, therefore, a diversion of electrons. If the B anode current increases, the A anode current must decrease. Similarly, a decrease of the A anode current would always be accompanied by an increase of the B anode current. This effect is conditional on the existence of saturation in the tube. Since by increasing the potential of the main anode A we have diverted electron current to the anode B, the main anode current decreases.

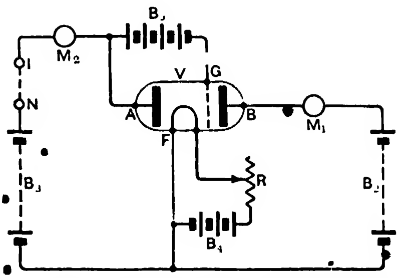


FIG 366.—A circuit which possesses negative resistance characteristics by virtue of the action of a negatron valve

There are now two effects which govern the A anode current; the increase in the A anode potential tends to increase the A anode current; the diversion effect, however, tends to decrease the A anode current. The diversion effect greatly outweighs the other, and the result is a decrease in the main anode current consequent on an increase of the main anode potential. A decrease of the main anode potential makes the grid more negative and decreases the current to B; the A anode current consequently

increases. In this way the negatron acts as a negative resistance.

The negatron, as described, works only when the saturation effect is obtained. For this reason, a filament current rheostat is desirable, and the current through the filament is adjusted until the negative resistance effect is obtained. If the filament be too bright, there will be no "robbing" action; there will always be a plentiful supply of electrons around

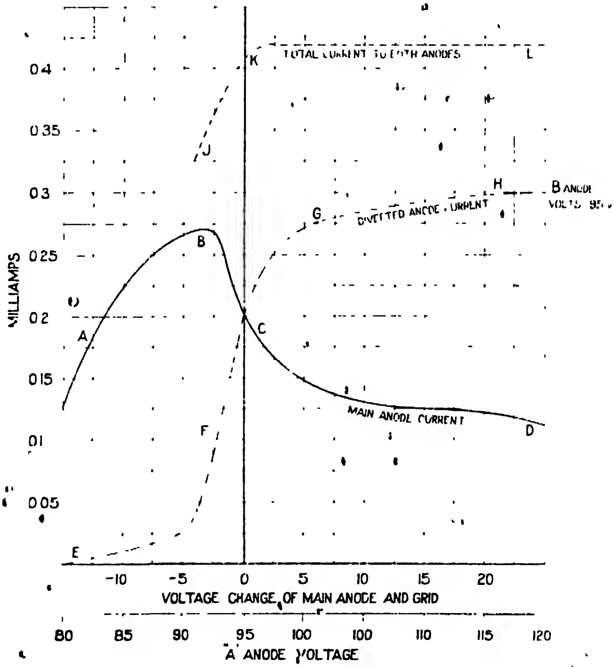


FIG. 367.—A set of characteristic curves which very clearly explain the "robbing" action which is necessary for the operation of the negatron.

the filament, and an increase of grid potential would increase the B anode current, and the additional electrons would come from the source around the filament and not from amongst those which would have gone to the main anode. The A anode current would, therefore, be unaffected and no negative resistance effect would be obtained.

The above explanation is borne out by characteristic curves obtained with the negatron, three of which curves are shown in Fig. 367. The thick line shows the main anode

current. The top thin curve shows the sum of the two anode currents. A broken line represents the diversion anode current. As the grid is always kept in the neighbourhood of zero volts, the grid current is almost zero. The grid is usually kept slightly negative, so that the grid current is zero. If this were not so, the grid current would add itself to the main anode current, and the negative resistance slope would be slightly less steep.

The curves of Fig. 367 bring out very clearly the "robbing" action which the negatron utilises. The top curve shows that the negative resistance effect is obtained while the tube is saturated. Since the total current remains constant and the diversion anode current increases (due to the control electrode potential rising), the main anode current must of necessity decrease, and this is shown by the thick line which slopes downwards. The main anode current decreases to the left of the peak because the saturation effect is non-existent (as proved by the top curve), and the decrease in grid potential produces an increase in space-charge circuit. The curve is, of course, only used along its downward sloping portion, and the oscillations will only be produced when the main anode and grid potentials are at suitable values. In practice, the grid potential is usually slightly negative, and no grid voltage adjustment is necessary.

To recount the applications of the negatron would take up too much space. The main use of it is as a generator of continuous oscillations for the transmission or reception of continuous waves. It may be used for receiving spark signals by reducing the effect of positive resistance. As a local oscillator it is exceedingly convenient, as it will oscillate on all ranges from 600 m. to 20,000 m. (the usual commercial range) without any complicated switching arrangements. The circuit arrangements which have been found most convenient are shown in Fig. 368. These are the same as those in Fig. 366, except that the two batteries are replaced by a single one B_2 of about 60 volts. The main anode A is connected through a leaky grid condenser C_2 to the grid G, a resistance R_1 being connected across grid and filament. This leaky grid condenser merely replaces the battery B_5 of Fig. 366 for the purpose of avoiding a high positive grid potential. The filament F is heated by current from the 6-volt accumulator B_1 through the rheostat R_2 of about 7 ohms' resistance.

This rheostat is adjusted until continuous oscillations are produced in the oscillatory circuit L_1C_1. It is to be noted that the diversion anode circuit plays no other part in the circuit than as a path round which electrons are shunted.

It will be of interest, no doubt, to demonstrate by means of curves the fact that the negatron only oscillates over a given range of filament current. Fig. 369 shows a series of characteristic curves; main anode currents are given for different values of filament current. The negative resistance effect disappears completely when the filament current is above 0·575 ampere. Likewise, it disappears, for an obvious reason, when the filament current is very small. An oscillatory

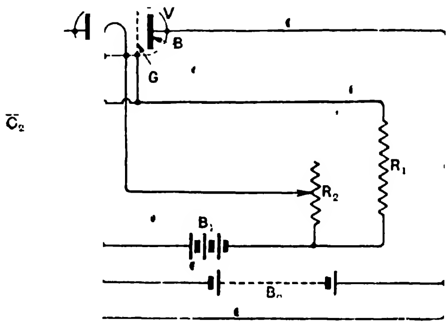


FIG. 368. A practical generator circuit employing a negatron vacuum tube: the rheostat R_2 is adjusted to the point where oscillations are set up.

circuit will oscillate provided conditions are such as to come within the shaded area, and no difficulty is experienced in practice through the limited range of filament brightness.

An Amplifying System using Two Valves. The accompanying Fig. 370 illustrates an interesting method of amplifying low-frequency current variations without any special coupling except that exerted by the electron path in the valve. Varying currents are applied to the grid G_1 of the valve A_1, which is included in series with the grid circuit of the second valve A. A battery B_1 produces an electron current through the valve A between F and G, the current then flowing between the filament F_1 and the anode P_1 of the first valve A_1. The effect of the varying potentials on the grid G_1 are to cause amplified variations of potential to appear on the grid G, and then these are amplified by the valve A and produce still larger variations

through the indicating device I, which may be a telephone

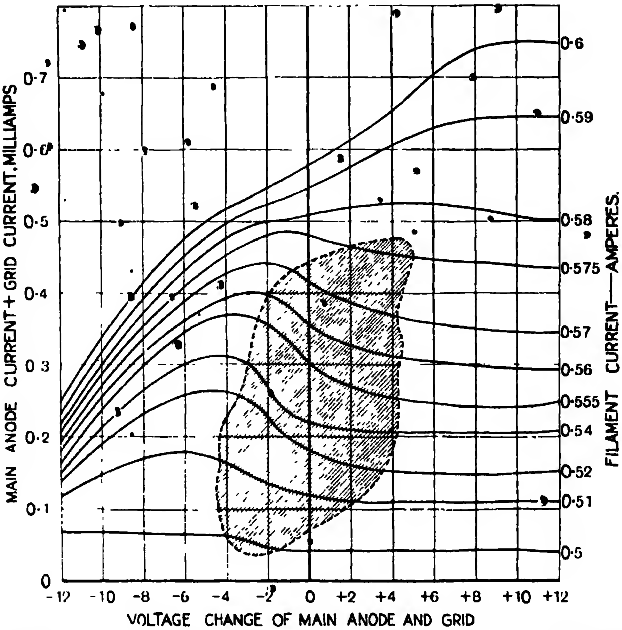


FIG. 369.—Characteristic curves showing why the negatron will only oscillate over a limited range of filament current.

receiver. This circuit is described in the author's British Patent 162710 of December 3, 1919.

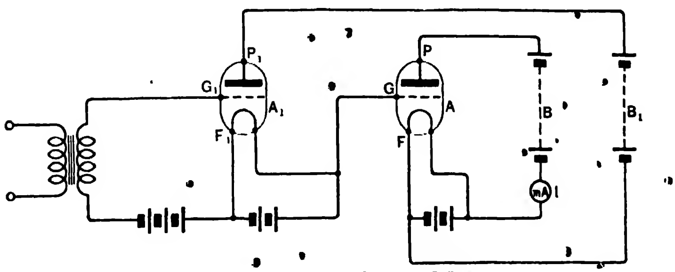


FIG 370.—A two-valve amplifier.

A Double-Grid Valve Receiving Circuit.—A very useful circuit for the reception of continuous waves, or, in fact, for any purpose, is illustrated in Fig. 371, which is taken from the author's British Patent 153681 of August 14, 1919.

A vacuum tube 19 contains an anode or plate 7, a control electrode or grid 6, another grid 18, and a cathode 5, shown as the filament, heated by a battery 8 through a resistance 9. An aerial inductance 1 is coupled to the inductance 2, which forms part of the closed oscillatory circuit 2, 3, which latter circuit is connected across the grid 6 and filament 5. The battery 4, or potentiometer, may be arranged to give the grid a suitable operating potential which should preferably be negative in order that there will be no damping of the oscillations in 2, 3 to the establishment of a grid current. In the plate circuit is the usual anode battery 10, inductance

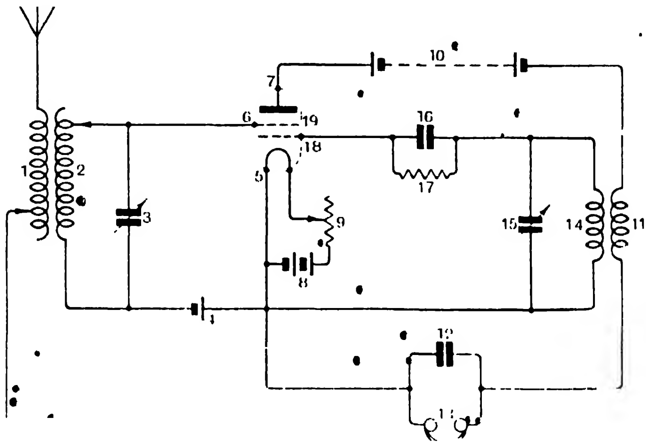


FIG. 371.—Double-grid valve circuit.

11, and telephone receivers 13, which latter are preferably shunted by a condenser 12. Across the second grid 18 and the filament is connected an oscillatory circuit 15, 14, which has in series with it a condenser 16 shunted by a high resistance 17. The inductance 14 is coupled to the inductance 11; when waves are received oscillations are set up in the circuit 2, 3, and cause magnified oscillations to be set up in the circuit 11, these magnified oscillations being induced into the circuit 15, 14, thereby varying the potential of 18 at the original frequency. The variations on 18 will vary correspondingly the plate current, and thereby a retroactive or regenerative action is obtained, strengthening the oscillations in 14, 15.

Owing to the action of the leaky grid condenser 16, these

oscillations are rectified, producing audio-frequency variations of the potential of 18, and thereby producing magnified audio-frequency variations of the anode currents which operate the telephones 13, a condenser 12 across which allows the free passage of high-frequency currents. By suitably adjusting the coupling between 14 and 11, these two circuits may be made to oscillate continuously at a frequency determined by the constance of the circuits.

If continuous waves are being received, the local oscillations may be arranged to form beats with the incoming signals, and audible signals will be heard in the telephones 12. It will be seen that the circuit 2, 3 may be tuned to the incoming wave-length, whereas in most circuits the closed receiving circuit is due to a slightly different frequency causing inefficiency.

From the above it will be seen that the grid 6 is used for amplifying, while the grid 18 is used in connection with the rectifying process. It may, however, be desirable to eliminate 16, 17 and 13, 12, and use the second grid 18 also in an amplifying manner, the oscillations in 11 being unrectified and capable of being passed on to a detector or further amplifying devices.

A Novel Relay Device.—The present author in British Patent 168394 describes a relay device in which a two-electrode valve is used.

A two-electrode thermionic valve is used, and input currents are passed through the filament and either heat it up to incandescence or vary its existing degree of incandescence. A general change in the current to the anode is produced, the anode being maintained at a steady positive potential with respect to the filament. In operating this relay it is proposed to pass the alternating, or other currents, through the filament of the two-electrode valve, the filament of which is preferably normally cold, or if heated, preferably not above the temperature at which electrons commence to be emitted. Across the anode and filament is connected a direct current-indicating device such as an ammeter or relay, and a battery so connected that the anode is given a positive potential with respect to the filament. Under normal conditions the filament is cold and no current passes through the indicating device. The amplified currents pass through the filament, and if sufficiently strong they will heat the filament to a degree of incandescence. Electrons will now be emitted by the

filament and will flow round the anode circuit and operate the indicating device.

When the current ceases to flow through the filament the anode current is automatically cut off and the indicating device returns to its normal state.

The device has many applications. In general, it will indicate the presence of current of an alternating nature as well as direct currents, but its chief application appears to be its use for indicating the presence of oscillatory currents. For example, by the use of trigger relay devices whereby an electrical impulse causes a vacuum tube to set up oscillations in its associated circuit, by including the filament of this device in one of such associated circuits the generation of oscillations will be indicated by the operation of the relay or indicating device.

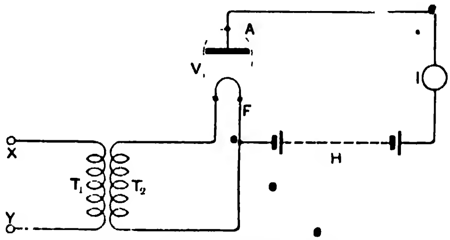


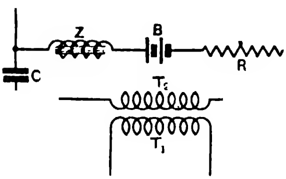
FIG. 372.—A novel relay.

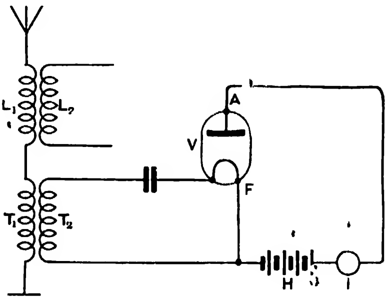
By connecting the filament of the device in the antenna circuit of a wireless transmitting station, the presence of oscillations in the aerial will be indicated by the operation of, say, an ammeter included in the anode circuit of the device. The intensity of the energy in the aerial circuit may be gauged by noting the reading of the ammeter. In this way the relay device may be used as an aerial ammeter, and it might be calibrated by the passage of direct currents of known strength through the filament.

Fig. 372 shows the valve V containing a filament F and an anode A, a battery H and a direct current indicator I being connected across the two electrodes. The filament F is heated by means of input currents, and these, if of an alternating nature, may conveniently be supplied to the transformer T_1T_2, the input currents being led to the terminals XY. When the input currents heat the filament F it becomes incandescent and emits electrons. A direct current consequently

flows in the anode circuit and operates the direct current indicator I, which may be a galvanometer relay or other device operating off direct currents. Currents used to heat the filament may be of any nature, but the invention will have special utility as a detector of oscillating or alternating currents.

To render the apparatus more sensitive, the filament may in its normal state be heated to a temperature just below that at which electron emission commences. This may be done by a local battery, and a method suitable for use of high-frequency detection is shown in Fig. 373. The filament circuit includes a battery B, a variable resistance R, and a coil Z to choke back high-frequency currents and force them to pass through the





FIGS. 373, 374.—Showing uses of relay.

filament. The winding T_2 and condenser C, together with the filament, complete the oscillatory circuit.

Fig. 374 illustrates the use of the device as a high-frequency ammeter. The filament may be connected directly in the aerial circuit, or may be an oscillatory circuit coupled to the antenna as shown. The oscillations in the antenna circuit are shown induced into it by means of the transformers L_1L_2.

A Novel Negative Resistance Device.—The author has produced a novel negative resistance device which has several interesting features. The invention is illustrated by Figs. 375 to 378. A valve containing two anodes and a cathode is so arranged that the current from the cathode is distributed between the anodes and so that a rise in potential of one of the anodes is accompanied by a decrease of current to that

anode owing to a diversion of current to the other anode, the diversion being due to an increase in the potential of the other anode. The second anode circuit preferably acts only as a means of diverting the electron current.

The apparatus is so arranged that when the first anode has its potential increased, a second increase is communicated to the other anode, so that the potential applied to the second anode, even if not greater than the potential applied to the first, will nevertheless have the stronger electrostatic attraction for the electrons around the cathode, and will consequently draw electrons away from the first anode, whereby decreasing the currents in the first anode circuit. This robbing effect is obtained when the total current to the anodes remains substantially constant and equals the total electron emission from the cathode, which is usually an incandescent filament.

The best conditions for operation may be obtained by adjusting the filament current until the robbing effect is given. In order that for similar potential changes on the anode the different distribution of electrons shall take place, it is arranged that the second anode is preferably closer to the filament than the first or main anode. It is possible to obtain the results desired by amplifying the potential increase to the first or obtaining some kind of amplifying effect so that the second anode is given a higher potential than the first anode, and therefore draws away currents which would have gone to the first anode. The current which is then drawn away from the second anode flows round to the cathode without usually being utilised in any way whatever. The current, of course, must not flow to the cathode through the points in the first anode circuit between which a negative resistance effect is desired.

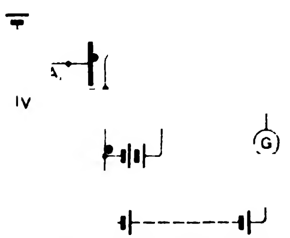


FIG. 375.—To explain control

Fig. 375 shows a thermionic valve V_1 having a filament F, two anodes A_1 and A_2. The anode battery B produces an electron current from F to A_1, through V and round F. Likewise the anode battery H produces an electron current from F to A_2 round through the galvanometer, or measuring instrument G, and the battery H to F. The electron current from F is now distributed between the two anodes, and our desired

effect is most marked when the electron emission from F equals the sum of the two anode currents. If we gradually increase the potential of A_1 from a negative value upwards, a characteristic curve of the valve will be somewhat as shown in Fig. 376. At first the current to A_2 will increase, as shown by the curve ABC of the curve ABCDE. A point, however, will soon be reached when the anode A_1, being positive, will begin to draw away electrons from the anode A_2. This point is shown just beyond the curve, and beyond the saturation point C the current to A_2 decreases as shown by the portion CDE of the curve. At the same time the current to A_1 is increased.

This phenomenon is well known in the arc, and the effect is obtainable with the ordinary three-electrode valve when the

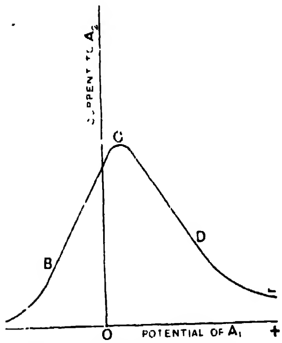


FIG. 376.—Characteristic curve.

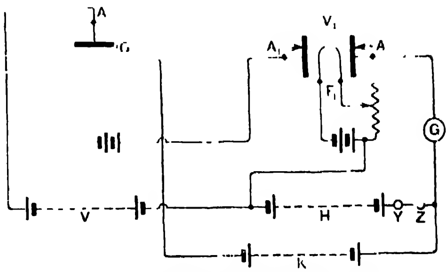


FIG. 377.—Negative resistance circuit.

grid potential is high. It is proposed to utilise this robbing action, due to the increase of one anode potential, to produce a negative resistance effect. It is proposed to operate the valve at some such point D on the downward slope of the characteristic curve.

The two anodes are preferably in the form of flat plates, one on each side of the filament.

Fig. 377 shows a practical way of arranging two valves to obtain a negative resistance effect. The valve V_1 is preferably constructed so that the two anodes are arranged one on each side of the filament. In the A_2 anode circuit is the galvanometer G and battery H. In the A_1 anode circuit is a valve V_2, the filament F_2 of which is connected to the anode A_1, and the anode A_2 of which is connected to a battery B and a filament F. The electron current from F now passes to the

two anodes A_1 and A_2. The current to the anode A_1 passes through the three-electrode valve V_2 to the filament F. The current round this circuit may be controlled by altering the potential of the grid G_2. If the grid G_2 is made positive a greater current will flow round this circuit, or expressing it in another way, the anode A_1 would be more positive. Similarly, if the grid G_2 be given a negative potential the anode A_1 will become less positive. The grid G_2 is connected so that any electromotive force in series with H which might be applied, for example, across the terminals YZ, would be communicated to G_2.

Suppose, now, we connect a battery across YZ so as to act in series with H, the anode A_2 becomes more positive, and we would expect, if this circuit possessed positive resistance

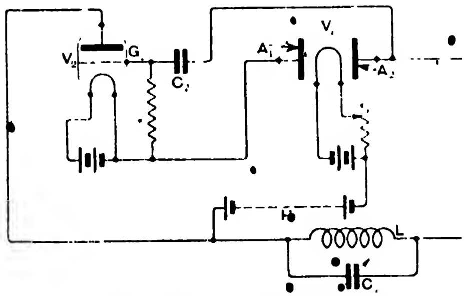


FIG. 378.—A generator circuit.

characteristics, that the current round the A_2 anode circuit would increase. At the same time, however, the grid G_2 is made more positive, thus making the anode A_1 more positive, and this increase of potential of A_1 diverts electrons which would have passed to A_2. These electrons pass round the A_1 anode circuit and are inoperative. To obtain the best diversion effect it will usually be desirable to connect a variable resistance in the filament current circuit so as to produce a saturation effect which is favourable to the diversion phenomenon.

Owing to the diversion of current to A_1 the anode current to A_2 decreases so that change of current through YZ is in an opposite direction to that expected.

To obtain a negative resistance effect in the circuit to lessen its positive resistance it is only necessary to include such circuit between the terminal YZ.

Fig. 378 shows a practical arrangement of the circuit for

the purpose of producing continuous oscillations. The oscillatory circuit LC_1 is connected in the AT anode circuit of the valve V_1, and a grid condenser C_2 is connected in series with the grid G_2 of the valve V_2. This enables us to do away with special batteries for preventing high voltages on the grid.

CHAPTER XVII.

A NEW INVENTION FOR SELECTIVE RADIO RECEPTION AND THE MINIMISATION OF ATMOSPHERIC INTERFERENCE.

The following description is an abstract of a Paper read by the present author before the British Association, September, 1923:

A STAGE in the history of radio telegraphy has been reached when those engaged in communication work view with grave concern the future prospects of the art. Atmospheric interference remains an important problem, and the ether is becoming congested.

The ether is rapidly becoming filled with wireless signals of all wavelengths, from 50 metres to over 20,000 metres. Even at the present day, not a little difficulty is being experienced in separating desired signals from those of stations working on adjacent wavelengths.

The syntonisation of wireless receiving apparatus has progressed considerably since the remarkable early work of Lodge and Marconi. The introduction of high-frequency tuned amplifiers has enabled a very high degree of selectivity to be obtained. The use of reaction has also contributed, in no small measure, to the success of modern selective receiving apparatus. Note-frequency tuning has also been elaborated and used for commercial long-distance communication.

The greatest achievement, however, in selective reception is unquestionably the method of continuous wave reception known as the "heterodyne" system, invented by Fessenden. By this beat method of receiving continuous waves, not only is greater selectivity achieved, but a pure, musical signal is obtained which lends itself to selective reception on tuned low-frequency circuits.

In spite, however, of 27 years of research work and commercial experience, even those with the most intimate

knowledge of modern developments regard the future with a certain amount of apprehension. E. F. W. Alexanderson, the Chief Engineer of the Radio Corporation of America, a month or two ago made the following remarks :

"It can now be readily seen that since the ability to receive distinct signals depends on the separation of different frequencies, there is a definite limit to the number of 'channels' of communication between stations that can be set up.

"If the wavelengths between 11,000 and 22,000 metres are divided into 2 per cent. bands, there are 35 'channels.' If into 1 per cent. bands, there are 70 'channels.' Except to such extent as directional reception will permit, the number of one-way channels open for such long-distance communication is limited to the number of these bands.

"The congestion of the ether is, therefore, not a mere matter of looking into the future, but a real present-day problem. The necessity for traffic regulation—at least enough to prevent reckless driving, so to speak—is just as apparent as the undesirability of hidebound regulations until such time as the limit of possible improvements in technique have been more definitely determined.

"Such is the present situation in the long-distance radio ether. The congestion is due to the necessity for the use of the longer waves for long-distanced work, and the fact that all high-power stations are broadcast stations ; much improvement is possible in existing practice, but radically new methods of operation must also be considered."

Having pointed out the immediate need for new methods of selective reception, a few remarks regarding present-day methods will not be out of place.

Present-day Methods.—When receiving continuous waves it is usual to take advantage of two, and often three, methods of selective reception. In the first place, the signals are more or less selectively received by means of high-frequency tuned circuits, valve amplification being used for the purpose. Heterodyne reception is employed to convert the radio-frequency currents into musical notes which will operate telephone receivers or other indicating apparatus. Instead of applying the low-frequency signals directly to the telephone receivers, or like apparatus, note-frequency tuning is often resorted to. In view of the musical notes received by the heterodyne method of reception, the advantages of

both high- and low-frequency syntonisation are obtainable. No mention has been made of directive aerial systems, but these are commonly employed in long-distance communication.

That Fessenden's invention has its limitations is disputed by none. Heterodyne reception, remarkable as it is for the selective reception of short wavelengths, is of comparatively little value for the reception of the waves commonly used for long-distance communication. Nevertheless, the beat method of reception, even for long wavelengths, is a sensitive one, and also provides a pure musical note, or, rather, low-frequency currents of regular wave-form.

The very important fact, however, remains that the full advantages of heterodyne reception are not realised on the longer wavelengths. This, of course, is very unfortunate, as long-distance communication is carried out usually on wavelengths between 10,000 and just over 20,000 metres. These waves have been found to be most suitable for communication over long distances.

The comparative failure of the heterodyne system on commercial wavelengths used for trans-oceanic communication has left us dependent, very largely, on methods of eliminating signals which involve resonance phenomena which were applied to selective reception 26 years ago.

"The two great landmarks in the history of selective wireless reception are the utilisation of resonance phenomena and the reception of continuous waves by means of the production of beats. The time has now come when these trusted methods are no longer sufficient. To-day governments are becoming more and more reluctant to issue new wavelengths for radio communication. The ether is already overcrowded, and the allocation of any new wavelengths only makes matters worse. There is, with modern apparatus, a limit to the extent to which wavelength channels may be adjacent to each other. A certain number of kilocycles have to separate the frequencies of two different stations if they are not to interfere with each other. This means that on the longer wavelengths there has to be a greater difference in wavelength between the different stations and only a relatively small number of high-power stations can communicate on the band of wavelengths between 10,000 and 20,000 metres. In other words, on the longer wavelengths, unless existing methods are altered, it will only be possible to have a certain

number of transmitting stations, and this number will soon be completed.

We cannot increase the wavelength used indefinitely, owing to innumerable factors, and even if we could, the problem of selective reception would become worse and worse, owing to the necessity of separating out the wavelengths of the stations farther and farther apart.

A New Invention.—Having outlined the shortcomings of present-day apparatus, I propose to give a very brief outline of an invention which I patented in May, 1920, but which is publicly described to-day for the first time.

The principle is of such a basic character that its application may affect the whole trend of methods of selective reception.

The invention involves the increasing, at the receiving station, of the frequency difference between desired and undesired currents. This method of solving the problem of selectivity and atmospheric elimination has never yet been attempted or suggested. The frequencies have remained the same, and the methods which have been adopted have been calculated to separate the desired from the undesired frequencies without attempting to change the actual frequency of either.

According to part of my invention, the frequency of the incoming currents is increased, with the result that the frequency difference between currents of different frequencies is increased.

An example will explain more readily what is meant. Let us assume that two stations are working on wavelengths of 15,000 metres and 15,100 metres. The wavelength difference, in this case, amounts to 100 metres, a very narrow margin, and one which, under ordinary circumstances, would lead to the 15,100-metre signals jamming the 15,000-metre signals. If now we apply both sets of incoming currents to a frequency multiplier giving a multiplication of, say, 10 times, currents will be delivered to the receiver by both sets of incoming currents. The 15,000-metre desired signals will set up oscillations corresponding to a wavelength of only 1,500 métres, while the 15,000-metre signals will be resolved into signals corresponding to a wavelength of 1,510 metres. There will now be 10 metres' difference between the two signals, but 10 metres' difference on a wavelength of about 1,500

metres is ten times more valuable than a difference of 100 metres at a wavelength of 15,000 metres.

The number of cycles' difference is the controlling factor in considering selective reception without interference. The example of the 15,000-metre signals being jammed by the 15,100-metre signals may be understood more clearly if we deal in cycles of frequency instead of metres. The 15,000-metre desired signal will set up oscillations having a frequency of 300,000,000 divided by 15,000, which equals 20,000. The 15,000-metre signals will correspond to oscillations having a frequency of 19,868. The frequency difference, therefore, is only 132 cycles.

If now, instead of receiving these signals in the ordinary way as, for example, by the heterodyne method, we multiply the frequencies of both signals by 10, we will increase the frequency of the signals due to the 15,000-metres station to 200,000 cycles, this corresponding to a wavelength of 1,500 metres. The 15,100-metres' interfering signals will produce interfering oscillations having a frequency of 198,680 cycles.

It will be readily appreciated that the difference between the new desired and undesired currents is now ten times as great, and equals 1,320 cycles. Where before we had to differentiate between signals having a difference in frequency of only 132, we now have the considerably easier task of separating out signals having a difference of frequency of as much as 1,320 cycles. Put crudely, it is ten times as easy to separate out the two stations.

The new currents of multiplied frequency may be applied to selective high-frequency receiving circuits, and the heterodyne method of reception may be employed.

Frequency Multiplication and the use of Beats.—It needs very little imagination for a student of these matters to appreciate the remarkable selectivity which is obtainable by a combination of frequency multiplication and heterodyne reception. A theoretical circuit is illustrated in Fig. 379.

In this figure, it is assumed that in the aerial circuit, which contains the inductance L_1 and variable condenser C_1, we have two sets of oscillations. One set has a frequency of 20,000, corresponding to the wavelength 15,000 metres of the desired signals, and the other currents have a frequency of 19,868, corresponding to the interfering signals of 15,100 metres. The circuit is turned, of course, to the frequency

of 20,000, corresponding to the desired signals, but nevertheless this method of selective reception is grotesquely ineffective when the frequency difference is so small. The next stage in the process is to apply the two sets of currents to a frequency multiplier which is shown, for the sake of convenience, as a box FM. This frequency multiplier may take many forms, and might be a series of frequency-doubling devices, such as valves, or it might be an apparatus for producing harmonics, a selected harmonic being then treated as the fundamental for reception purposes. The output currents from FM pass through the oscillation circuit L_2C_2, and even here resonance tuning may not be sufficient. Loose coupling between L_2 and L_3 will, however, if the primary and secondary circuits are tuned to the new 200,000-frequency signals—which are

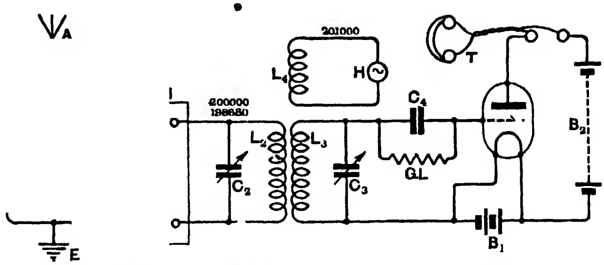


FIG. 379.—Reducing interference by frequency multiplication.

really derived from the original 20,000-frequency signals by a multiplication of 10—cause the 198,680-frequency currents, due to the interfering signal which originally had a frequency of only 19,868, to be less effective.

Oscillations are now induced into the circuit L_3C_3 from the heterodyne H, which may be, for example, a valve oscillator. This heterodyne induces local oscillations having a frequency of 201,000. The result of inducing currents of this frequency into the circuit L_3C_3 will be the production of two sets of beats. The 201,000-frequency oscillations will beat with the desired 200,000-frequency oscillations producing beats of 1,000 frequency, and these beats will be rectified and detected by the valve V, in the output circuit of which are the telephone receivers T. The 1,000-frequency beats will, of course, produce a musical note in the telephones T having a frequency of 1,000, which is a very convenient frequency for the reception

of continuous wave signals. The 201,000-frequency oscillations induced by the local heterodyne, will also produce beats with the oscillations having a frequency of 198,680 which, it is assumed, have not been tuned out by the use of resonance phenomena. The beats, in this case, will have a frequency of 2,300.

We now have in the telephones T two sets of signals. The desired sets have a frequency of 1,000, while the undesired ones have a frequency of 2,300, and no difficulty should be experienced in reading the desired signals without material interference from the other signals. It is important to notice that the incoming signals are not, of course, simply steady streams of continuous oscillations, but consist of dots and dashes of short duration, and that during a considerable

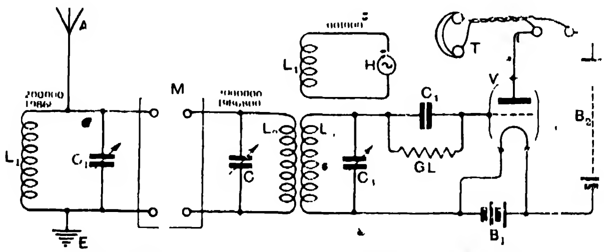


FIG. 380.—Frequency multiplication of 100 times

period of time, dots and dashes of the undesired signals are received during the intervals between dots and dashes of the desired signals.

Hundredfold Multiplication.— A far more striking example of the possibilities of this new principle in wireless reception is when we consider the frequency multiplication to be, say, 100 times. Such conditions are illustrated in Fig. 380.

The frequency multiplier FM now increases the frequency of the desired signals to 2,000,000, corresponding to 150 metres, while the interfering signals now have their frequency raised to 1,986,800. The frequency of the local oscillations of the heterodyne are adjusted to 2,001,000. With the desired currents of 2,000,000 frequency, the heterodyne currents will produce beats of 1,000 frequency which will produce a musical note of 1,000 in the telephone receivers. With the interfering signals, the local oscillations will produce beats having a

frequency of 13,300. This frequency, to all intents and purposes, may be treated as above the audible limit, and the desired signals would therefore be received in the telephone receivers without any interference whatever from the undesired signals, even though in the initial aerial circuit the frequency difference amounted to such a small amount as 132 cycles.

The advantages to be gained from the method outlined in this Paper are supplemented by resonance tuning, and in practice a frequency multiplication of 100 times would not be necessary. It will readily be appreciated that even a multiplication of only 2 will double the difference in frequency between desired and undesired signals. This means that we can increase the "elbow room," as it were, for signals of any particular wavelength, and greater selectivity is thereby obtained. Alternatively, we can say that by doubling the frequency of the incoming signals we can have twice as many channels of communication in any given band of wavelengths. If, for example, we take Alexanderson's figure of 35 channels of communication between 11,000 and 22,000 metres, by frequency doubling we can increase this to 70. By multiplying the frequency 10 times, we could have 350 stations working between these two extreme wavelengths. If we multiply the frequency of signals 100 times, we could have 3,500 stations working.

By the application of this invention to long-distance communication, it would therefore seem that the problem of the congestion of the ether has been solved.

While this method of reception marks a third stage in the progress of selective reception, both resonance tuning and beat reception retain all their former usefulness; in fact, heterodyne reception becomes even more important as it now becomes a really effective process in the reception of continuous waves of great length. One way of looking at the invention which is the subject of this Paper is to consider that the long wave signals are brought down to the lower wavelengths where the full advantages of beat reception, as regards selectivity, are obtained. The lower the level to which we bring the incoming signals, the more selective does heterodyne reception become.

Application to Low Frequencies.—So far, the application of the method to high-frequency signals only is described. The principle, however, is just as applicable to audio fre-

quencies as to radio frequencies. The author's experiments in this direction have fully borne out theoretical expectations, and two signals having a note frequency imperceptibly different have been entirely separated in such a way that one of the frequencies is entirely suppressed.

Such a very remarkable achievement could not be obtained, or even approached, by any other method which has hitherto been proposed. Its significance, of course, is that note tuning becomes a reality; almost the whole of the selective apparatus may be concentrated on the low-frequency side of a wireless receiver. When receiving continuous waves, even the slightest differences between two sets of continuous oscillations will produce different beat notes with a local heterodyne. These will give rise to slightly different audio frequencies which would seriously interfere with each other and entirely prevent the selective reception of a desired signal.

Where existing methods cannot differentiate between signals of slightly differing pitch, it is possible by this invention to magnify their difference to such an extent that either signal may readily be read without interference.

The original audio-frequency signals have their frequency stepped-up by means of harmonic producing, or other frequency-multiplying apparatus, to a radio frequency which should preferably be well above the audible limit. These radio-frequency currents may now be selectively received by the aid of tuned high-frequency circuits and then combined with local radio-frequency continuous oscillations. These local oscillations are produced by a heterodyne, beats being produced. All the advantages of high-frequency tuned circuits and beat reception are thereby obtained, and whereas the original difference in frequency might be only 100 (barely perceptible) the final difference in frequency might be 10,000, a frequency which would enable the interfering signals to be cut out entirely.

Fig. 381 shows a theoretical wireless receiving system in which the invention is applied to the low-frequency currents. The high-frequency signals are rectified by the crystal D producing audio-frequency currents through T_1, due to the fact that a local oscillator H_1 induces continuous oscillations into the aerial circuit of a frequency slightly different from that of the desired signals. The currents of musical frequency passing through T_1 are then applied by means of the transformer

T_1T_2 to the frequency multiplier FM, in the output circuit of which we have a circuit L_2C_2 tuned to a multiple of the desired audio-frequency currents passing through T_1. The circuit L_2C_2 will be a radio-frequency circuit, and the frequency of the currents in L_2C_2 should preferably be above the audible limit. The circuit L_3C_3 is tuned to the same frequency, and by loosely coupling L_2 to L_3 a certain amount of resonance selectivity is obtained. The principal method of obtaining the selectivity, however, is by the introduction of local oscillations produced by a second heterodyne H_2 tuned to produce currents having a frequency differing by, say, 1,000 from the currents in L_3C_3. The beats of about 1,000 frequency are now detected by the valve V and produce a musical note in T. The b produced by the interaction of the local

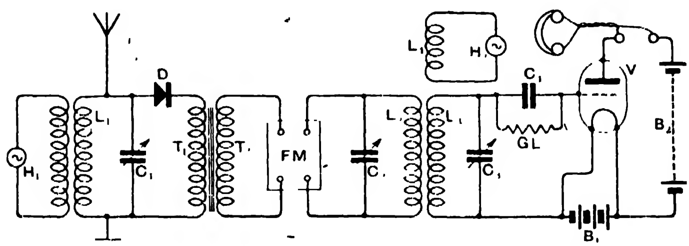


FIG. 381.—Multiplication of low-frequency currents.

oscillations supplied by H_2 and the undesired signals of multiplied frequency are arranged to be above or below the audible limit so as not to interfere with the desired signals.

A Combined High- and Low-Frequency Selective System.—It is, of course, convenient to apply the invention to both the high- and low-frequency sides of a wireless receiver, and Fig. 382 shows a simplified arrangement illustrating the different stages in the reception of continuous waves by this system. It will be seen that the first frequency multiplier FM_1 is for the purpose of increasing the frequency of the original oscillations. The oscillations of multiplied frequency are then heterodyned by H_1 and detected by the valve V_1, producing musical low-frequency currents. The output currents from the valve V_1, which will be of musical frequency, although, of course, it is not necessary that this should actually be so, are communicated to the second frequency multiplier FM_2; the frequency is once more stepped-up so as to reach

above the audible limit and the currents are selectively received by the aid of loose coupled circuits and the second heterodyne

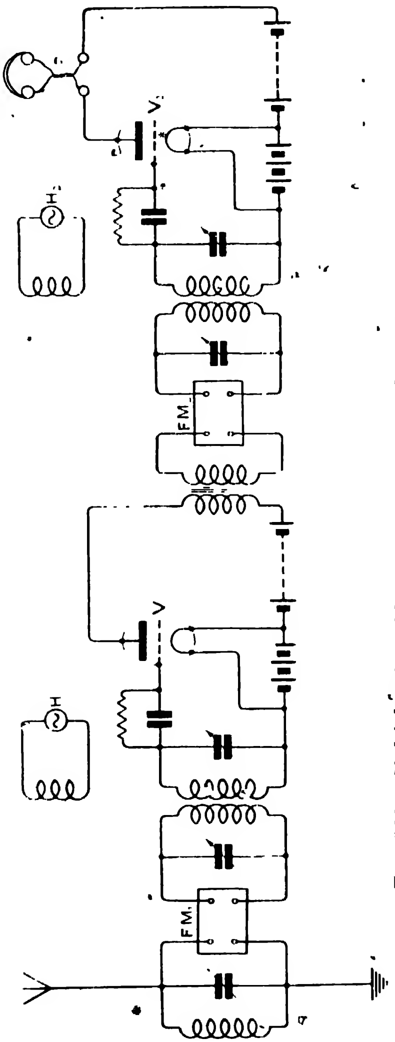


FIG 382.—Multiplication of both the high- and the low-frequency currents.

H_2, which enables a musical note to be obtained in the telephones.

The Apparatus Employed.—It is not possible within the scope of this paper to deal with the various practical circuits

for achieving the desired results. The method of obtaining the multiplied frequency is not, of course, an essential part of the basic invention. Thermionic valves, operated under special conditions, have been found suitable for producing harmonics or merely for doubling the input frequency. If harmonics are used, a considerable factor of multiplication may be obtained.

Fig. 383 indicates how the invention might be applied to the reception of incoming waves. The valve V_1 is operated at, say, saturation point, so as to produce harmonics in its output circuit L_2C_2, which is tuned to one of these harmonics. The valve V_2 is a self-heterodyne receiver which then receives the desired harmonic and treats it as the signal to be received.

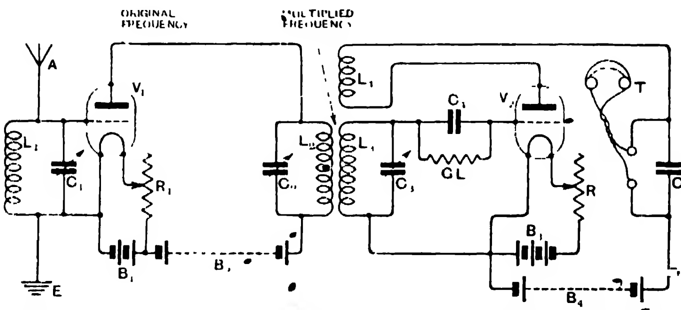


FIG. 383.—An application of frequency multiplication to a practical circuit.

The present Paper is only intended as an outline of the new system, and at some future date it is hoped to give further technical details.

The Minimisation of Atmospheric Interference.—The system of reception lends itself particularly to the elimination, or rather minimisation, of atmospherics. While this is probably, at the present date, the most important advantage of the system, yet it is mentioned at this stage of the Paper because this process of atmospheric elimination is essentially one of selectivity. The application of the method of frequency multiplication to the low-frequency side of a receiving circuit will automatically cut out all, or most, of the atmospherics, owing to the fact that most atmospherics have lower frequencies than the heterodyne notes due to desired signals. Unless their frequency exactly corresponds with the heterodyne

note, the process of frequency multiplication and resonance, combined with further heterodyning, will eliminate the atmospheric interference.

By the application of the method to the high-frequency side of the receiving apparatus, the effect of atmospherics may also be minimised by causing them to produce oscillations (for example, by the impact excitation of a detuned circuit) different from the incoming continuous waves. Frequency multiplication increases the divergence between the two different signals, and in any case currents of the wave-form of atmospherics will not readily produce effective harmonics.

A Novel Method of Receiving Continuous Waves.—The author's British Patent 192429 of August 8, 1921, describes several circuits for receiving continuous waves which involve interesting principles.

Fig. 384 shows one of the circuits. It will be seen that a

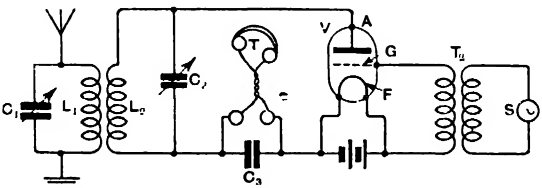


FIG. 384.—One method of receiving continuous waves.

three-electrode valve is used, the oscillatory circuit L_2C_2 being included between the anode of the valve and the filament, telephone receivers T being also in this circuit. To the grid circuit is applied a varying current from F, this current being usually of low frequency, or of a frequency slightly different from the incoming frequency. If the currents supplied by F are of audible frequency, the note will be reproduced in the telephones T when the incoming continuous wave signals feed the anode circuit of a valve. When these currents are not applied to the anode, practically nothing is heard in the telephones T. If the currents supplied by F are of radio-frequency, they may be adjusted to a slightly different frequency from the incoming signals, in which case beats will be obtained, these operating the telephones T and producing a musical signal in them.

Fig. 385 shows another circuit in which the source of alterations S may be made to supply high-frequency currents

of continuous wave form, having a frequency slightly differing from the incoming frequency. As before, the telephones T will emit a musical note corresponding to the beat frequency.

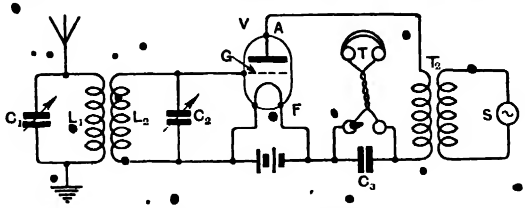


FIG. 385.—Another arrangement.

Fig. 386 is a modification of Fig. 384, a potentiometer

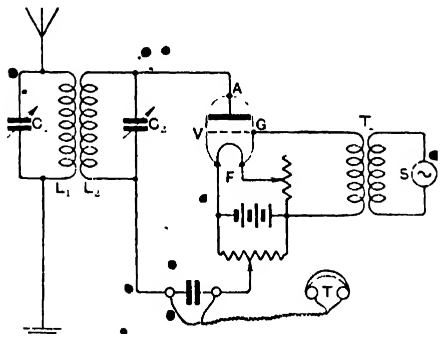


FIG. 386.—Another continuous-wave receiver.

being employed to vary the normal potential of the anode of the valve.

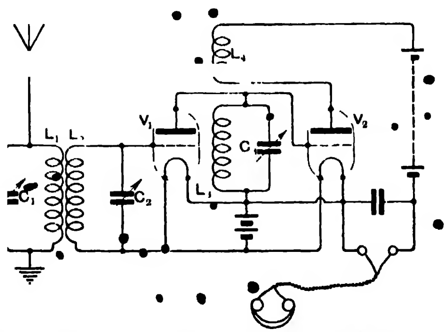


FIG. 387.—A further circuit for continuous-wave reception.

Fig. 387 shows another method of receiving continuous

waves. A valve V_2 acts as a local oscillator and is preferably adjusted so as to produce currents having a slightly differing frequency from the incoming currents. No high-tension battery is included in the anode circuit of the first valve. The telephone receivers T may be connected in the anode circuit of either the first or second valve.

A Mechanical Reaction Relay.—Fig. 388 shows a mechanical reaction relay described by the author in his patent 172757 of September 24, 1920. In the figure, A represents a milliameter or other similar device, to the end of which is fixed a moving electrode S which moves, preferably in

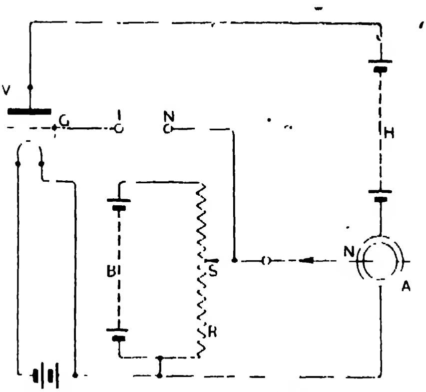


FIG 388. The mechanical reaction circuit.

liquid resistance R. The moving contact S is insulated from the needle N. The input potentials are applied to the terminals IN, and cause a slight variation of the potential of the grid G, in, we will assume a positive direction. There is a resultant increase in the anode current which will, we assume, cause the needle N to move upwards. The needle will carry the contact S upwards, with the result that a larger positive potential is applied to the grid G by the special potentiometer arrangement BR. In this way a reaction effect is obtained, and very slight potentials applied to the grid G will be rapidly built up with a resultant large movement of the contact S. This might, of course, be used to close a local circuit in many different ways.

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